GEOPHYSICS

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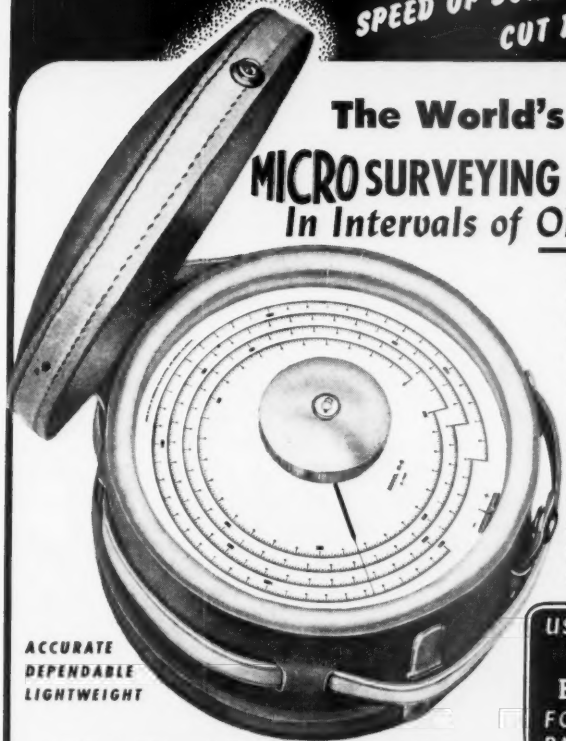

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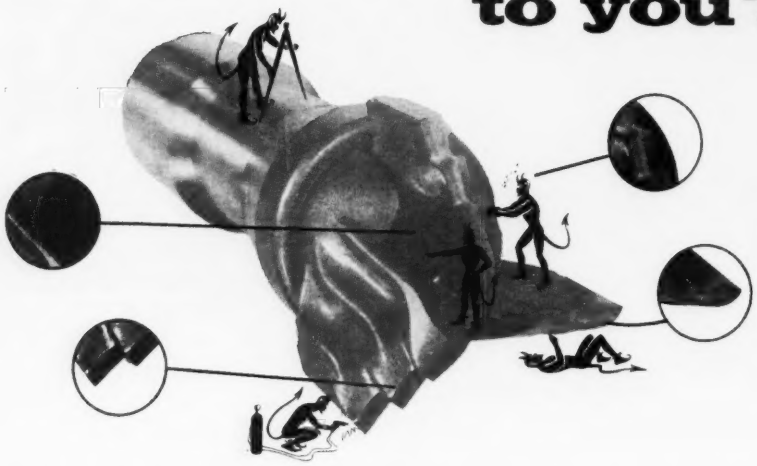

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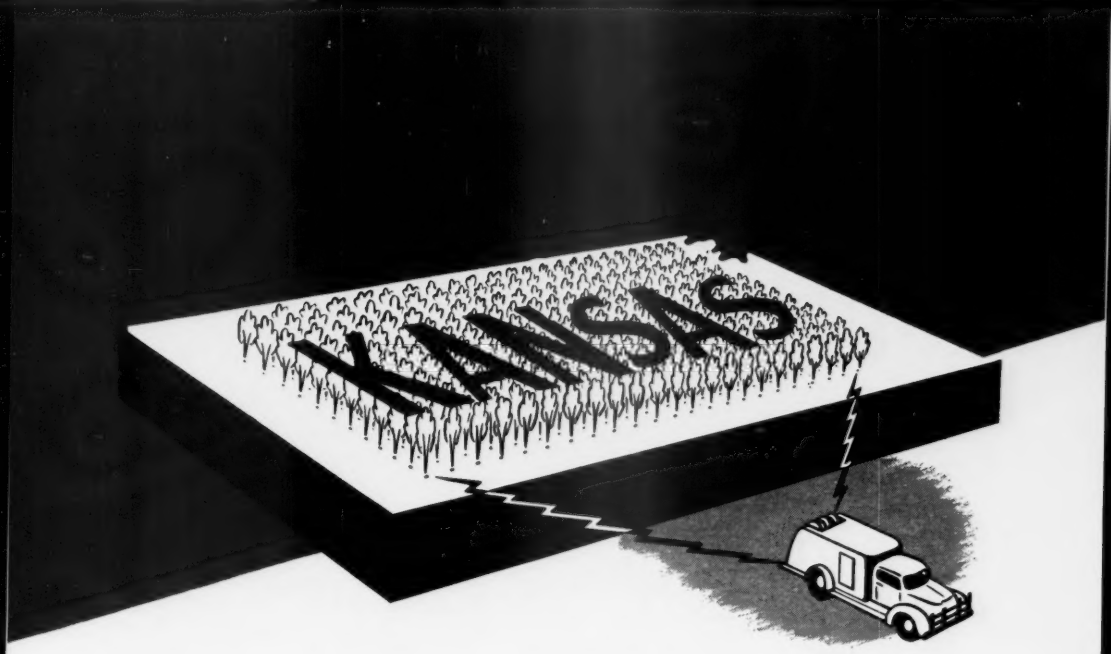

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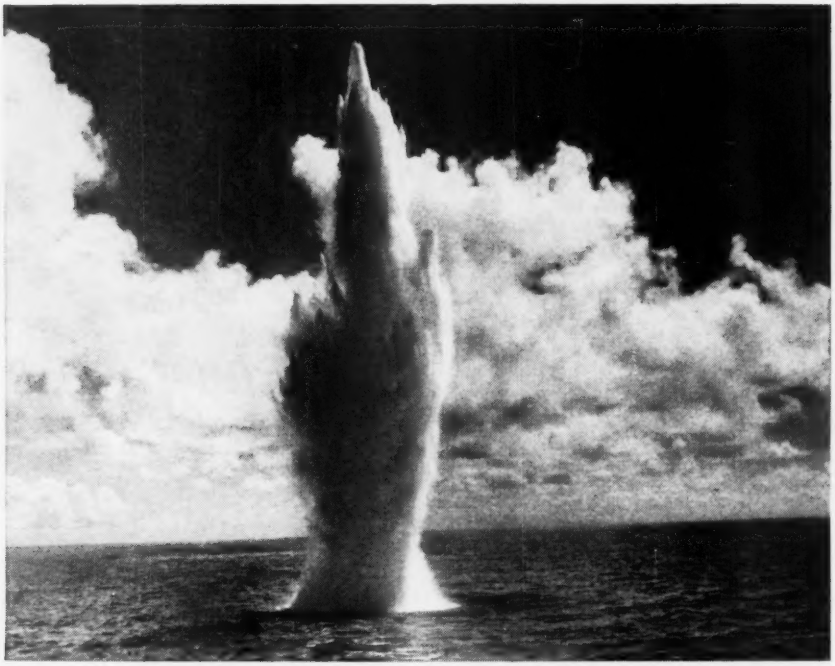

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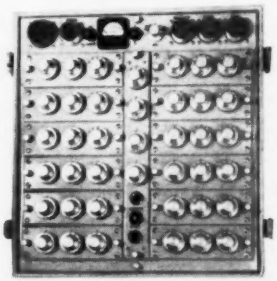

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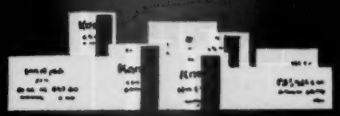

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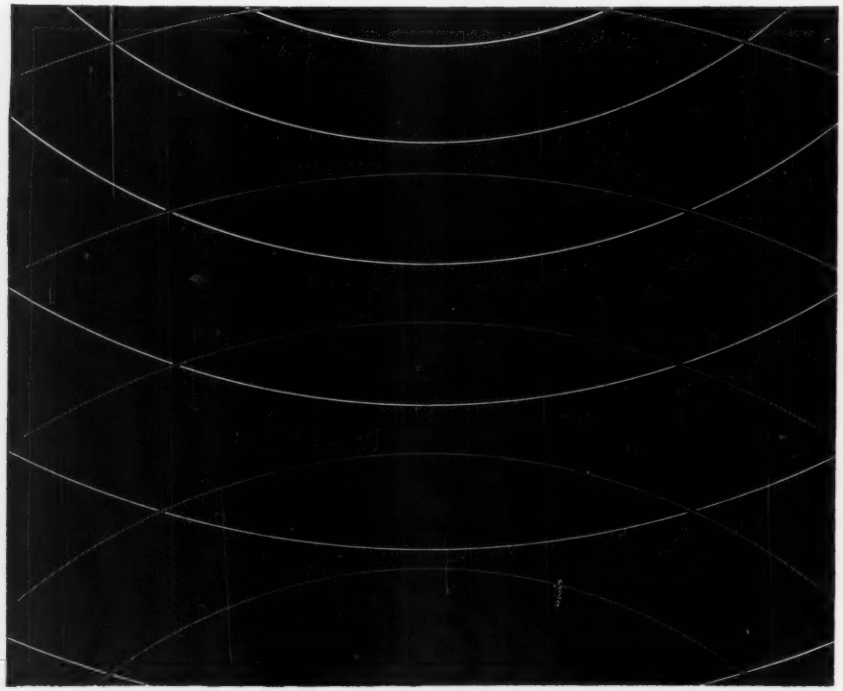

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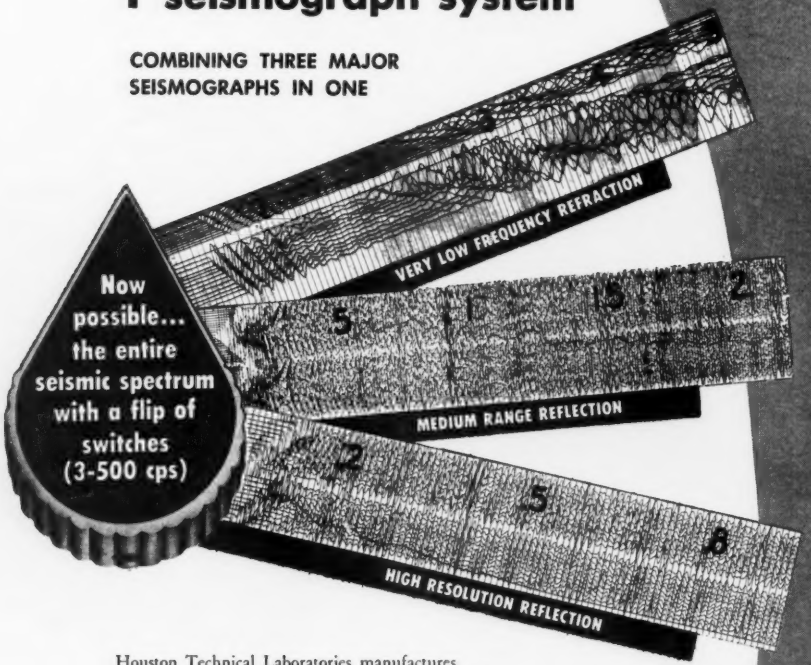
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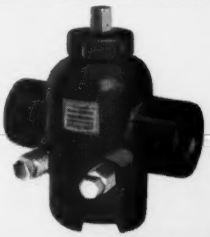

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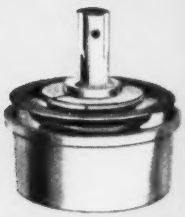

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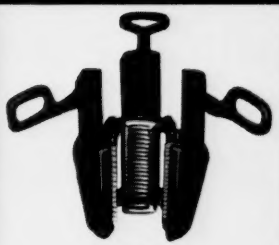

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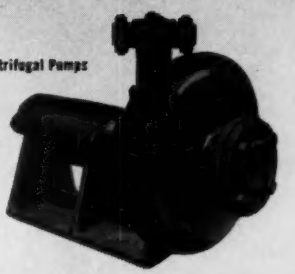

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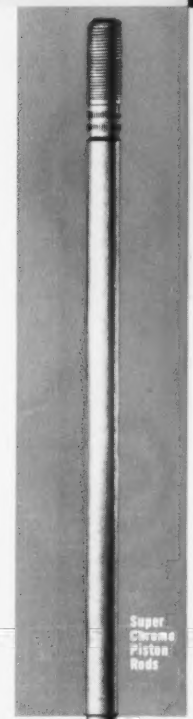

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GEOPHYSICS

TECHNICAL PAPERS

THE COMPOSITION OF REFLECTIONS*

J. P. WOODS†

ABSTRACT

When the traces on a seismic reflection record all show about the same deflection at about the same time, the line-up is marked and called a seismic reflection. An important fact is forgotten. The fact is that the reflection seen on the record is nearly always a composite of the various reflections caused by a set of closely spaced reflecting layers. When the arrangement of the layers in the set changes, then the various reflections add together in a different way, and the character of the composite reflection seen on the record changes.

A series of artificial seismic records have been made to show this composition of reflections. The records were made by connecting a standard reflection seismograph to an acoustic model. The model was a three hundred foot length of steel pipe with input and output transducers at one end. Records were made for a wedge, a pinch-out, a complex of thin layers, a sand bar, layers corresponding to well resistivity logs, and a regular layer system.

INTRODUCTION

To develop a theory or to teach that theory, it is necessary to simplify. Such simplification is too long retained. When one thick seismic layer lies over another thick layer, there is an isolated seismic interface which will cause a single seismic reflection. This idealized situation makes thinking and teaching easier. In practice, the seismic situation is just as complicated as the geological situation. If the log of a well shows that many thin layers of sand and shale lie underground, then a reflection record shot near the well will show reflections caused by the many sand-shale interfaces. However, these reflections will overlap and interfere with each other; each line-up on the record will be the sum of several reflections. The reflection record is a sort of seismic log of the underground, but it is a log which lacks the resolution of the electric log.

The reflection seismograph makes use of an elastic pulse which has a length of about three hundred feet. At some places in the earth, many thin layers may lie

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† The Atlantic Refining Company, Dallas, Texas.

within this three hundred foot length, and the reflections caused by these layers cannot appear on the record separately. Rather they appear as one reflection which is a composite of all the reflections of the set. In contrast, the electric log will show layers which are only a few feet thick. The interval velocity log will also show layers which are only a few feet thick. When it becomes necessary to correlate a reflection record and an electric log, a mistake is usually made. The electric log or the velocity log is searched for sharp breaks which will fit the depths at which reflections are seen on the record. The correlation would be much better if the electric log were first re-plotted by some smoothing device which would filter out the sharp breaks and reduce the resolving power from a few feet to a few hundred feet. In other words, the electric log should be "played back" through a low pass or band pass filter such that the band of wave lengths for the electric log is the same as the band of wave lengths for the seismic record. Correlation would then be easier and more reliable.

There are various circumstances under which reflections interfere with each other. Reflections from a set of thin layers have been mentioned. There may be interference between the top and bottom reflections of a wedge, a pinch-out, or a sand bar. Often, two pulses are generated by the shot, and the reflections caused by these two pulses will interfere. If the shot is fired in water, the secondary pulse is generated by collapse of the gas bubble, and it will have the same polarity as the primary pulse. If the shot is fired underground, the secondary pulse is generated by reflection from the base of the weathered layer or the top of the ground, and it will have the polarity opposite to that of the primary pulse. In some areas, there is a regular sequence of reflecting layers. The composition of reflections from such a sequence occurs in a regular way; the interference phenomena show a sort of resonance.

Seismic records taken in the field can be used to demonstrate the composition of reflections under these various circumstances. However a seismic record is complex; it contains too much data for demonstration purposes. Also, there is always some doubt about the disposition of the reflecting layers and the magnitudes of the reflection coefficients. Seismic records are bulky. It is difficult to show them to an audience or to reproduce them in a technical journal. For these reasons, it seems better to use an acoustic model to demonstrate the composition of reflections.

THE ACOUSTIC MODEL

There are several ways to make a model. An electric transmission line was first considered; an alternate would be an electric wave guide. Consideration was given next to the use of elastic pulses traveling in a three dimensional solid, or possibly a liquid. The final decision was to use a sound tube. This tube is shown in Figure 1. It is a steel pipe three hundred feet long and two inches in diameter. At the top of the pipe are mounted two transducers. One of these is a speaker into which is fed a short pulse of electric current. This causes the speaker to emit a

sharp click—the sound which corresponds to the dynamite explosion. The other transducer is a microphone. It corresponds to the geophone, and it is connected to a standard set of seismic reflection instruments.

This model was selected because it is simple and cheap, because it is easy to place a number of reflectors inside the pipe, and because the frequency range is

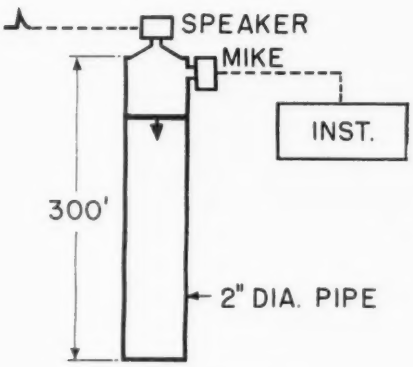


FIG. 1. Pipe and transducers.

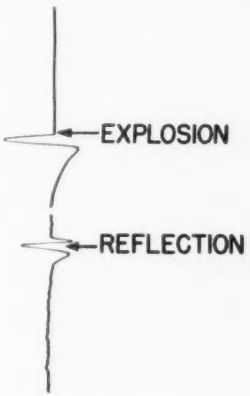


FIG. 2. Reflection record from pipe.

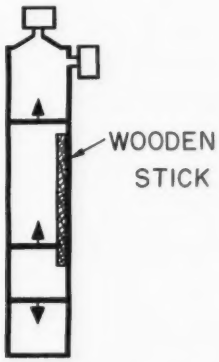


FIG. 3. Pipe, transducers, and wood insert.

such that standard seismic instruments can be used. The record produced is shown in Figure 2. The first deflection of the trace is caused by sound which travels directly from the speaker to the adjacent microphone; this is the instant of explosion or time break; it will be omitted on other records. The central portion of this record has been cut out, and timing lines have been omitted for the sake of

clarity. The second deflection of the trace is caused by sound which travels the length of the pipe, is reflected by the closed end of the pipe, and then travels back up the pipe to the microphone. The time break pulse and the reflection pulse have the same polarity, but this fact is not apparent because the time break pulse is badly distorted due to amplifier overload.

Of course, this is not a seismic model. The system is acoustical and one dimensional. There are no shear waves, no surface waves, and no divergence of energy. The attenuation of sound waves in the pipe is not the same as the attenuation of seismic waves in the earth. Further, the process of reflection in the sound tube differs from the process of reflection of seismic waves in the earth.

The pipe is seen again in Figure 3, and a wooden stick is shown placed inside the pipe. This stick is about one inch thick, two inches wide, and twenty feet long. The presence of the stick reduces the area available for the transmission of sound; the stick changes the acoustic impedance of the pipe. Hence, when sound travels down the pipe, a reflection will occur when the sound comes to the top of the stick, and a second reflection will occur when the sound comes to the bottom of the stick.

The characteristic impedance of the pipe is

$$z = \frac{Pc}{s} \tag{1}$$

where:

P = density of air;
c = velocity of sound in air;
s = area of the pipe.

The impedance of the pipe with the wooden stick is

$$z' = \frac{Pc}{s'} \tag{2}$$

where:

s' = area of the pipe minus the area of the stick.

The reflection coefficient is

$$r = \frac{z' - z}{z' + z} \frac{\frac{1}{s'} - \frac{1}{s}}{\frac{1}{s'} + \frac{1}{s}}. \tag{3}$$

For seismic reflection, the coefficient is

$$R = \frac{V'D' - VD}{V'D' + VD} \tag{4}$$

where:

V = velocity for the upper layer;
D = density for the upper layer;
V' = velocity for the lower layer;
D' = density for the lower layer.

If the densities are the same,

$$R = \frac{V' - V}{V' + V}. \tag{5}$$

Comparison of equation (3) with equation (5) shows that reflection in the sound tube arises from change in reciprocal area; reflection in the earth arises from change in seismic velocity.

The sound tube will now be regarded as an analog of the earth. For convenience in further discussion, quantities which belong to the earth will be associated with the sound tube. For example, it will be said that the wooden stick of Figure 3 represents a seismic layer 600 feet thick of velocity 10,000 ft/sec, the material above and below this layer having a velocity of 8,000 ft/sec. This is the situation shown at the left of Figure 4. The reflection coefficient for the top of the fictitious seismic layer is

$$\frac{10{,}000 - 8{,}000}{10{,}000 + 8{,}000} = \frac{1}{9}.$$

For the sound tube, if placing the stick in the pipe increases the reciprocal area by one fourth, the reflection coefficient for the top of the stick is

$$\frac{1\frac{1}{4} - 1}{1\frac{1}{4} + 1} = \frac{1}{9}.$$

The seismic layer is said to be 600 feet thick, and the stick is 20 feet long. Hence, the scale factor for distance is 30. The scale factor is

$$k = \frac{W}{w} = \frac{V}{v}\,\frac{f}{F} = 30 \tag{6}$$

where:

W = seismic wave length;
w = sound wave length;
V = seismic velocity;
F = seismic frequency;
v = sound velocity;
f = sound frequency.

The ratio V/v is about ten. The ratio f/F was taken as three; that is, records were taken with the sound tube at frequencies about three times the usual seismic re-

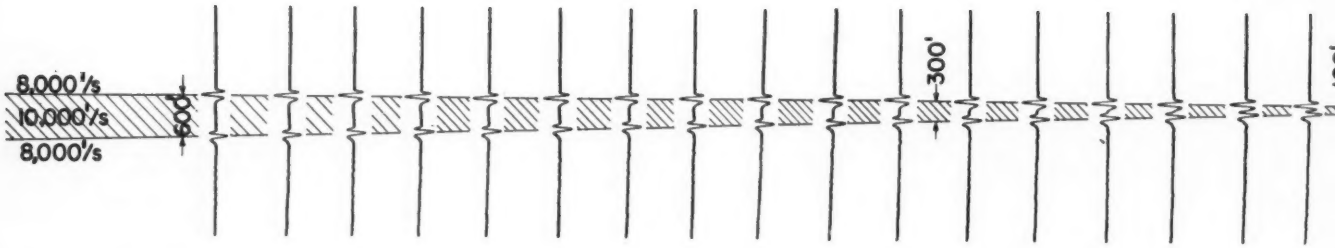


FIG. 4. Reflections from a wedge.

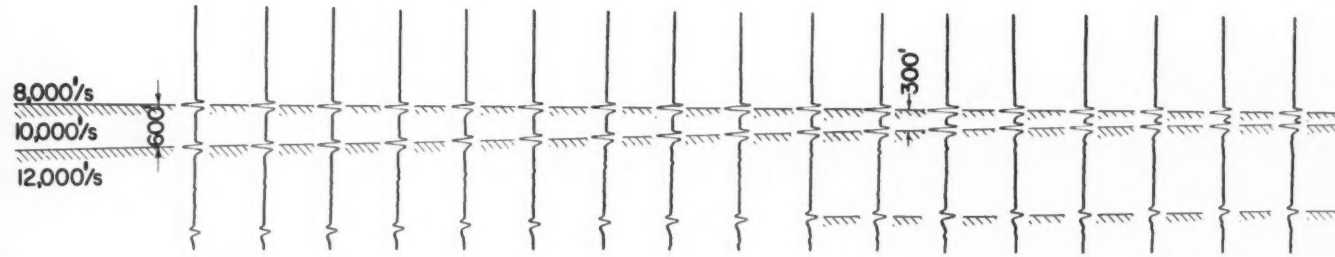


FIG. 5. Reflections from a pinch-out.

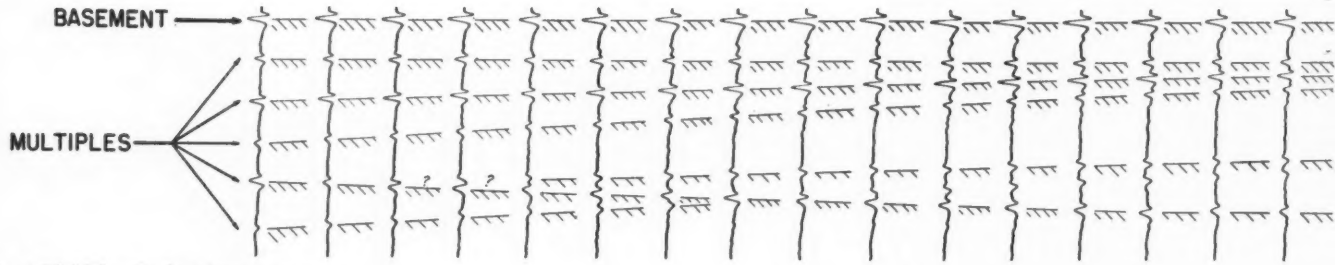
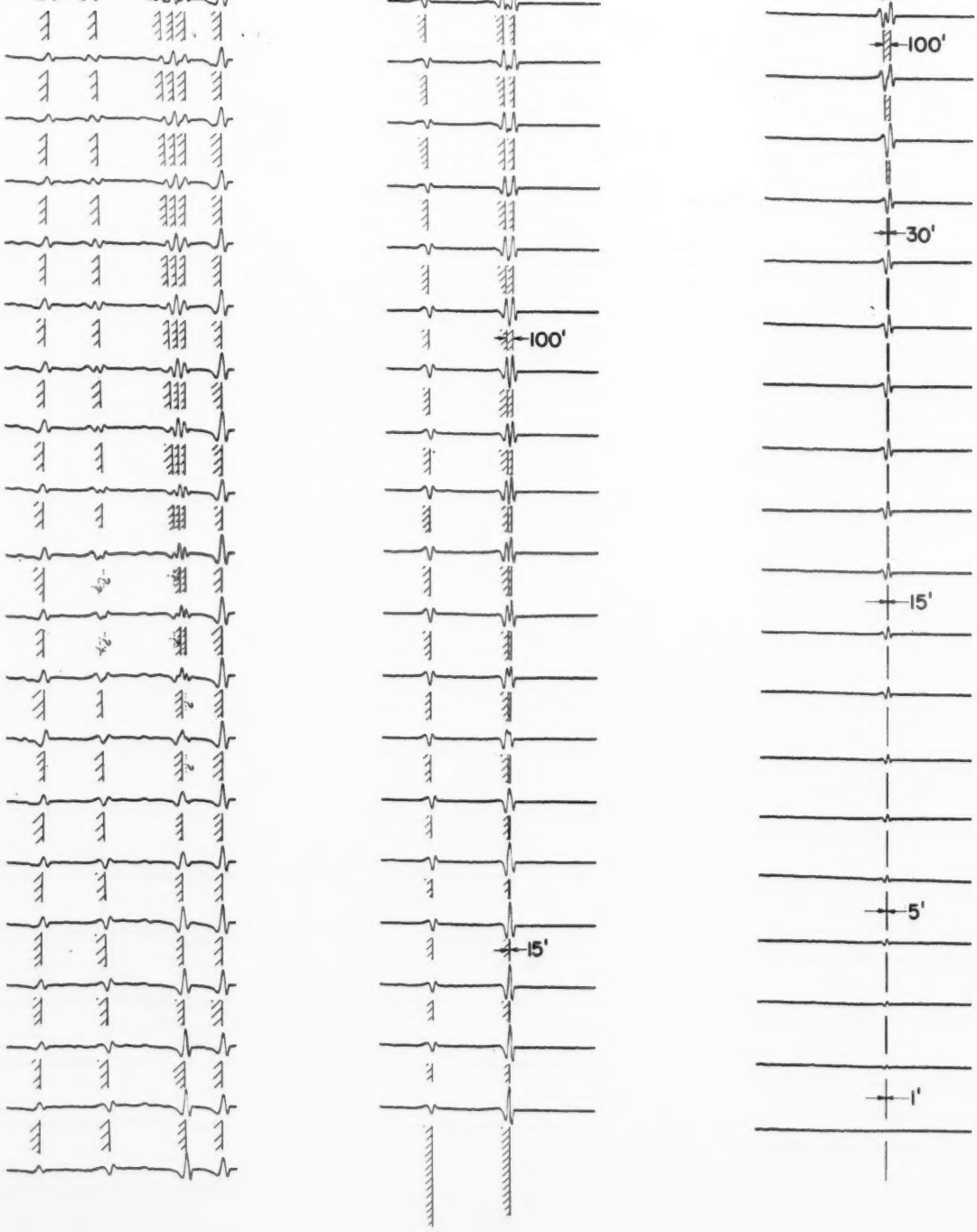


FIG. 6. Multiple reflections from a pinch-out.


100'
30'
100'
15'
15'
5'
1'

flection frequencies. Hence in going from the sound tube model to the earth:

(1) distances are scaled up thirty times;
(2) velocity is scaled up ten times;
(3) frequency is scaled down three times;
(4) time is scaled up three times;
(5) reflection coefficients remain the same.

Different combinations of wooden sticks were placed in the pipe to obtain the records which follow. These combinations will not be described. The discussion will proceed as if the records had come from the earth.

DISCUSSION OF RECORDS

Reflections from a Wedge

Reflections from a wedge are shown in Figure 4. Top and bottom reflections are of opposite polarity, because, in passing downward through the wedge, there is a velocity increase at the top interface and a velocity decrease at the bottom interface. When the wedge is less than 300 feet thick, the two reflections interfere. When the wedge is less than 100 feet thick, the two reflections appear as a single reflection which becomes smaller as the wedge becomes thinner. When the wedge is only one foot thick, there is still a visible reflection. This may seem surprising, but it must be remembered that on a true seismic record this small reflection would be obscured by other and much stronger signals.

Reflections from a Pinch-Out

Reflections from a pinch-out are shown in Figure 5. The layer of velocity 10,000 ft/sec is pinched out between an upper layer of velocity 8,000 ft/sec and a lower layer of velocity 12,000 ft/sec. The two reflections are of the same polarity because, in passing downward through the layer, there is a velocity increase at each interface. When the layer is 100 feet thick, the two reflections are seen to interfere. They can barely be resolved when the layer is 50 feet thick. Since the interference is additive, the two reflections merge into a single reflection of higher amplitude as the layer becomes still thinner. At last the pinch-out is complete, and there is left the single strong reflection caused by the 8,000 ft/sec layer and the 12,000 ft/sec layer.

Multiple Reflections from a Pinch-Out

In Figure 6 are shown the multiple reflections caused by the pinch-out and the bottom end of the pipe. Refer to Figure 3 and note that the bottom end of the pipe is closed. This closed end causes complete reflection of the sound. Continuing to regard the sound tube as an analog of the earth, the closed bottom end of the pipe will be called the basement. The analogy is not exact; in the sound tube, the closed end causes complete reflection; in the earth, the basement causes partial reflection. Hence, in the sound tube, the multiple reflections are stronger than they are in the earth. In Figure 6, the top reflection is the basement reflection. The

other reflections are multiples of the pinch-out reflections. An attempt has been made to correlate these multiples, and the correlation marks are shown in Figure 6. These marks are included to illustrate the difficulties which face the seismologist who makes the mistake of marking multiple reflections on a seismic record. The seismologist has the defense that he cannot tell a multiple reflection from a primary reflection. The defense is good, but it does nothing to lessen the difficulties.

Reflections from a Pinch-Out; Double Impulse from Shot

The acoustic model is shown again in Figure 7. There has been a change. The speaker is no longer at the top of the pipe but is now 6 feet down from the

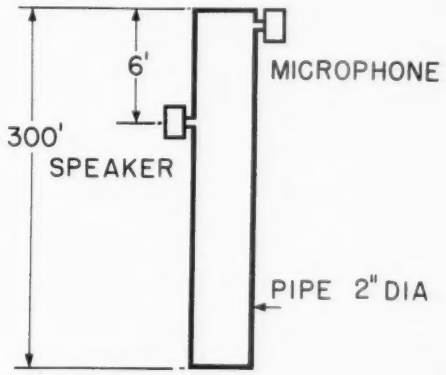


FIG. 7. Pipe arranged for two impulses of same polarity.

top. When current is fed to the speaker, two sound pulses will go down the pipe. The primary pulse goes from the speaker directly down the pipe. The secondary pulse goes up the pipe to the closed end at the top where it is reflected without change in polarity. It then goes down the pipe as a trailing, or secondary pulse. The situation is analogous to that when a seismic shot is fired in deep water. The explosion causes a primary, down-going seismic pulse, and it causes a gas bubble in the deep water. A fraction of a second later, the collapse of the gas bubble causes a secondary, down-going seismic pulse of the same polarity as the primary pulse.

In Figure 8 are shown the reflections from a pinch-out when the shot produces two pulses of the same polarity. When the 10,000 ft/sec layer is 600 feet thick, the reflection at each interface is seen as a doublet. At a thickness of 300 feet, interference begins. At a thickness of 200 feet, there appear to be three reflections, the center reflection being the strongest. When the layer is 100 feet thick, there are again four reflections; but this time the reflections are closely spaced and of different character. When the layer is 50 feet thick, the reflection is again seen as a doublet. As the layer continues to pinch-out, the reflection gradually becomes

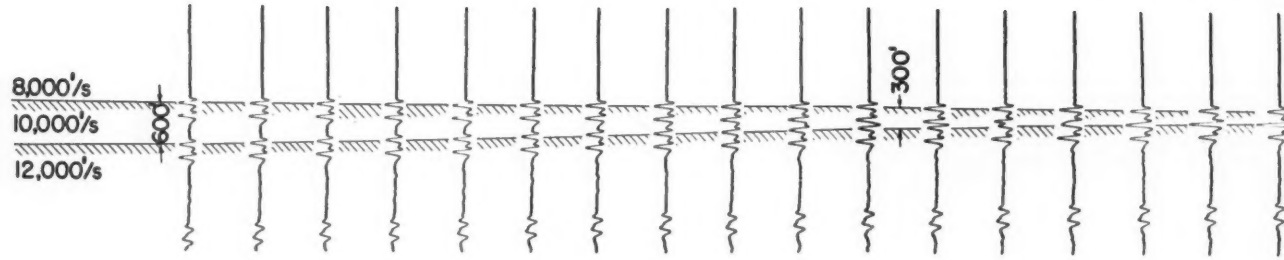


FIG. 8. Reflections from a pinch-out; double impulse from shot.

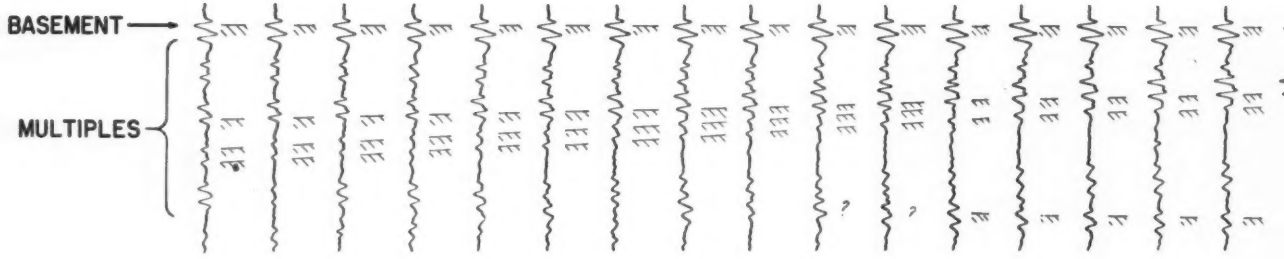


FIG. 9. Multiple reflections from a pinch-out; double impulse from shot.

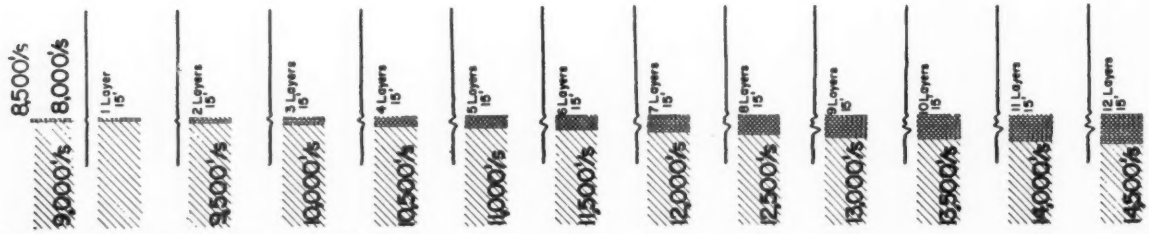


FIG. 10. Reflections from layers 15 feet thick.

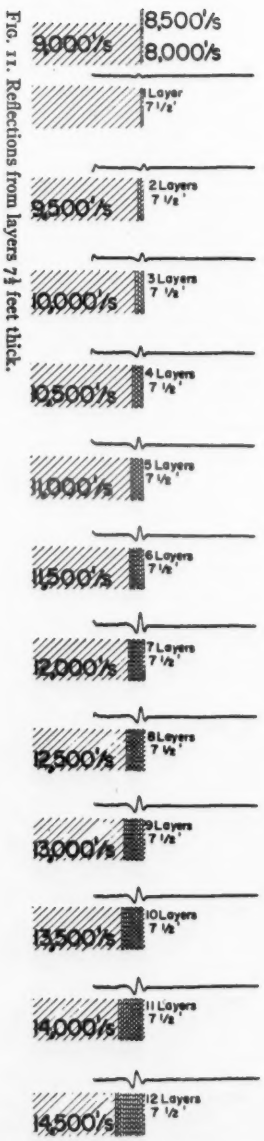
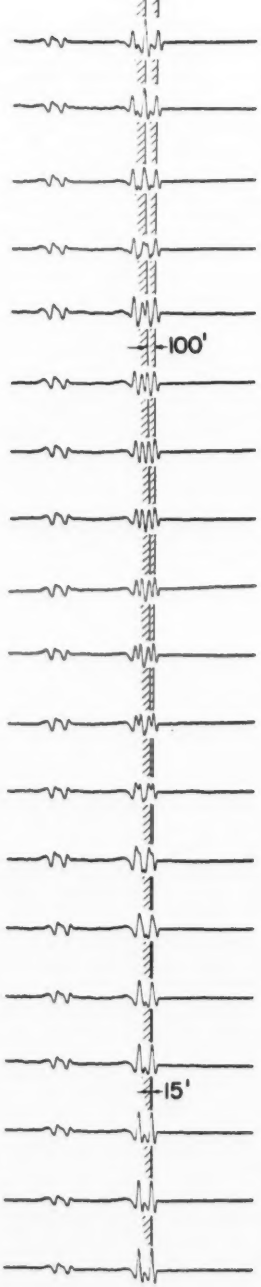


FIG. 11. Reflections from layers 7½ feet thick.



the doublet caused by the interface between the 8,000 ft/sec layer and the 12,000 ft/sec layer.

In field practice, changes in reflection character similar to those seen in Figure 8 may take place in records obtained from a profile stretching across miles of country. There will be differences, of course. Probably the shot will not be fired in water but will be fired in a deep shothole. This will produce a different sort of double shot impulse which will vary in character as shot depth is varied. Also, changes in the material near the shot will change the frequency content of the shot impulse. Moreover, changes in the near-surface material will cause variations in the always troublesome surface waves and will affect geophone response. Figure 8 presents the seismic data for a pinch-out in a total of 35 traces. If the actual seismic profile is 10 miles long, the seismologist may have to follow yet more complicated seismic data for a pinch-out through a total of 800 traces. At times, the seismologist's life is not a happy one.

Multiple Reflections from a Pinch-Out; Double Impulse from Shot

In Figure 9 are shown multiples of the pinch-out reflections when the shot produces a double impulse. The reflection at the top is the basement reflection which appears as a doublet because the shot impulse is a doublet. An attempt has been made to correlate the multiple reflections, and the correlation marks are shown in Figure 9. If such correlation marks were made on a set of seismic records taken in the field, perhaps the interpreter would be tempted to indicate a fault on his seismic cross-section.

Reflections from Thin Layers

Figure 10 starts on the left with a reflection caused by three layers. The thick layer at the top has a velocity of 8,000 ft/sec. The middle layer is 15 feet thick and has a velocity of 8,500 ft/sec. The thick layer at the bottom has a velocity of 9,000 ft/sec. The reflection is small. The second reflection shown is larger and is caused by four layers: a top layer of velocity 8,000 ft/sec; a layer 15 feet thick of velocity 8,500 ft/sec; a layer 15 feet thick of velocity 9,000 ft/sec; and a bottom layer of velocity 9,500 ft/sec. The third reflection is yet larger, and it is caused by five layers, the middle three layers being each 15 feet thick. And so the sequence is continued, one layer 15 feet thick being added at each step. As each thin layer is added, the reflection becomes larger. When there are eight thin layers, the reflection starts to become a doublet. At the end of the sequence, there are twelve thin layers, and the reflection is a doublet. There are now thirteen interfaces and two reflections. This should be a difficult situation for the interpreter who insists that for each reflection seen on the record there must exist underground a single, definite interface.

For Figure 11 the sequence of Figure 10 is repeated with the difference that each thin layer is now $7\frac{1}{2}$ feet thick instead of 15 feet thick. Again the reflection becomes larger as the number of thin layers increases. At the end of Figure 11,

there are twelve layers, but the reflection this time has not become a doublet, There are now thirteen interfaces and one reflection.

Linear Increase of Velocity with Depth

The next logical step is to make the layers infinitely thin. In Figure 12 is shown a graph of velocity versus depth. There are three layers. The top layer has

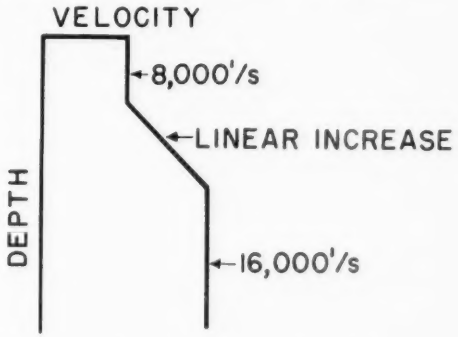


FIG. 12. Linear increase of velocity with depth.

a velocity of 8,000 ft/sec; the middle layer is 90 feet thick and has a velocity which increases with depth in linear fashion from 8,000 ft/sec to 16,000 ft/sec; the bottom layer has a velocity of 16,000 ft/sec. The reflection caused by this layer sys-

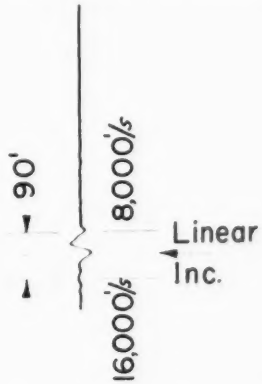


FIG. 13. Reflection due to linear increase of velocity.

tem is shown in Figure 13. Now there exists no interface at which there is a velocity jump; and yet there is a reflection. The reflection occurs because, within the layer 90 feet thick, velocity increases rapidly with depth. If the transition layer

were much thicker, velocity would increase slowly with depth, and there would be no reflection. Thus, if it takes place slowly enough, there can be a large velocity change, and yet there will be no reflection. The situation is analogous to that in which a tapered section is used to match two transmission lines of different impedances. If the taper is slow enough, there will be no reflection.

Sand Bar Lying on Limestone

Figure 14 shows a sand bay lying on limestone. The top layer will be called shale with a velocity of 10,000 ft/sec; the sand has a velocity of 6,000 ft/sec; and the limestone has a velocity of 16,000 ft/sec. Starting at the left of the figure, there is no sand. Going to the right, the sand increases in thickness, and the reflection becomes larger. The center of the sand bar occurs at the center of the figure. Here the sand is 60 feet thick; the reflection is large; and the reflection has developed the initial downward kick indicated by the two arrows. Thus the presence of sand is indicated by both an increase in size and a change in the character of the reflection. Going on to the right of the figure, the sand disappears, and the reflection returns to that caused by the shale-limestone interface.

Reflecting Layers Corresponding to a Resistivity Log

Refer to Figure 3 and note the wooden stick placed inside the sound tube. Figure 15 shows a photograph of that wooden stick after a curve has been cut into

FIG. 15. Log cut into edge of wood insert.

one edge of it. This curve has been scaled from the resistivity log of a well in East Texas. Of course, it would have been better to use a velocity log had such a log been available. However, there is a rough similarity between a resistivity log and a velocity log. Also, these are experiments made with a model to illustrate ideas; there is no attempt to offer quantitative proof of anything. And so to some degree of approximation, perhaps poor, the reflecting properties of the underground have been read from a resistivity log and cut into a wooden stick which is to be placed inside the sound tube.

Resistivity Log and Reflections

Starting at the left of Figure 16, the first curve is the resistivity log of the well. This curve is for the depth interval 5,500 feet to 7,000 feet, and it can be seen

more clearly as the curve on the right of Figure 17. The second curve of Figure 16 shows the reflections which occur when the wooden well log is inside the sound tube. The label 17-60-B means that the seismic amplifiers were set for a band width of 17 cps to 60 cps using a single section filter. The letter "S" occurs later in the figure and designates a two-section filter. The third curve of Figure 16 is the well log repeated; the fourth curve is the reflection record with the seismic amplifier set for a band width of 17 cps to 85 cps using a single filter section. It must be remembered that in going from the sound tube to the earth, frequency

FIG. 17. Resistivity cross-section for seven wells.

is to be scaled down by a factor of three. Hence the frequencies shown in Figure 16 should be divided by three. At the left of the figure, there appear to be certain correlations between the log and the seismic record. At the right of the figure the correlations between the log and the record appear to be different because the filter has been changed. The seismic record is a composite of many reflections; the manner of making the composition is strongly influenced by the filter.

Cross-Section for Seven Wells

Figure 17 shows a resistivity cross-section for seven wells in East Texas. The wells lie on a line about 9 miles long. The four or five resistivity kicks near 6,500 foot depth are caused by the massive anhydrite which also causes a good seismic reflection. Figure 18 shows the records obtained from the sound tube model for this line of wells. The reflection caused by the anhydrite has been marked by three dashes. The upper and lower dashes indicate trace deflections which can easily be correlated across the seven wells. The middle dash indicates a trace

deflection which changes character gradually in going across the seven wells. Here then is that elusive thing called "reflection character" which an interpreter tries so hard to see in seismic records. The anhydrite reflection seen in Figure 18 is a composite of the dozen or more reflections caused by the layers which can be

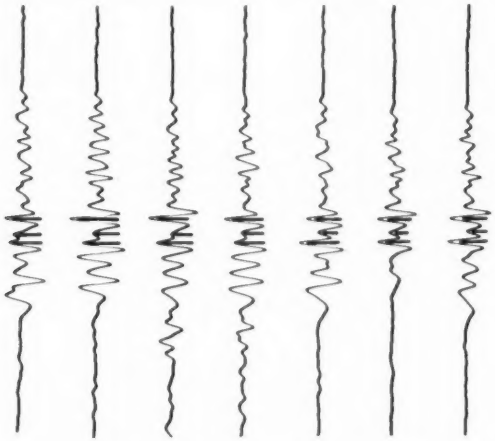


FIG. 18. Seismic cross-section for seven wells.

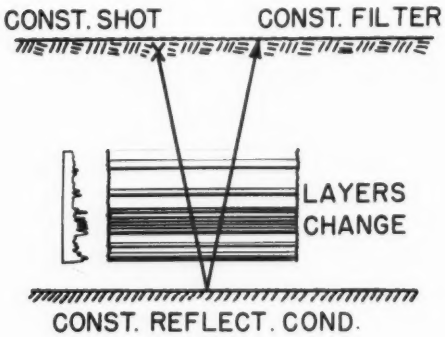


FIG. 19. A layer below the cross-section.

seen in Figure 17 in the interval 6,300 ft to 6,700 ft. The arrangement of these layers changes in going from one end of the line to the other; hence reflection character changes.

A Layer Below the Cross-Section

Figure 19 shows a deep reflecting layer which lies below the bottom of any of the wells of Figure 17. Assume that there are constant reflecting conditions at

FIG. 20. Reflections from a layer below the cross-section.

this layer; assume also that there are constant conditions at the shothole and constant conditions at the instruments. Will the reflection from this deep layer change when the line of seven wells is shot? If there is a change, it must be caused by the layers which lie above the deep reflection; that is, the layers which are shown by the resistivity logs of Figure 17. The reflections from this deep layer are shown in Figure 20, and there is a change in amplitude and character as the line is traversed. This change occurs because each reflection from a layer which lies above the deep layer robs the down-going shot impulse of energy. This energy depletion process is a function of frequency; and the frequency function depends upon the layer arrangement. Hence, when the shot impulse arrives at the deep reflecting layer, it has a frequency content which has been influenced by all the layers through which it has traveled. After reflection from the deep layer, the impulse is further altered in size and shape by going back through the layers above. Thus the character of a reflection is determined, not only by the particular group of layers which produce the composite reflection, but also by all of the reflecting layers which lie above that group.

A Regular Layer System

Figure 21 shows a system of six layers of velocity 14,000 ft/sec which are regularly disposed in a medium having a velocity of 10,000 ft/sec. The layer thick-

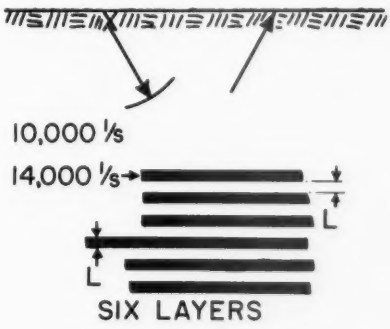


FIG. 21. A regular layer system.

ness is "L" feet, and the separation of the layers is also "L" feet. This system is regular enough to exhibit the phenomenon of resonance. At the left of Figure 22 is shown the reflection record when L is 100 feet. Next is shown the record when L is 95 feet, and so on. The reflection amplitude increases until the distance L

becomes 50 feet, and then it decreases. Note the way the reflections from these six layers interfere with each other. Since there are twelve interfaces, there should be twelve reflections. Half of these should kick down; the other half should kick up. Referring to the left of Figure 22 ($L = 100$ feet), it will be seen that an interpreter, picking down kicks in the usual way, would mark only four of these twelve reflections. Following across Figure 22, it will be seen that the reflections from these twelve interfaces degenerate into two reflections when the distance L becomes small. There is then a down kick at the top of the layer system and an up kick at the bottom. An interpreter would pick only the down kick.

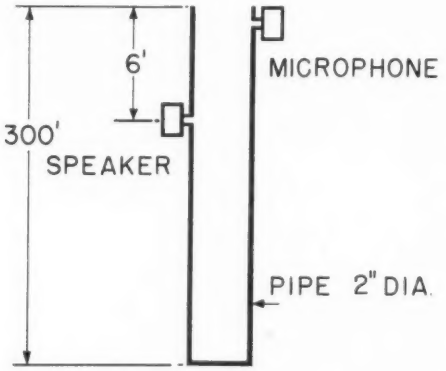


FIG. 23. Pipe arranged for two impulses of opposite polarity.

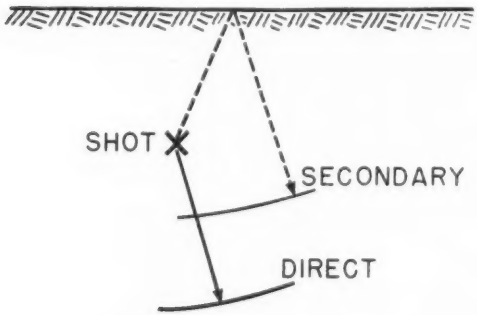


FIG. 24. Direct and secondary impulses.

Primary and Reflected Shot Impulses

In Figure 23 the sound tube is shown arranged to give a primary shot impulse followed by a secondary shot impulse of opposite polarity. The secondary impulse will be of opposite polarity because it is reflected from the top end of the

pipe which is open. Figure 23 is to be compared with Figure 7. The doublet impulse produced by the arrangement of Figure 23 corresponds to the doublet impulse obtained when a shot is fired in a deep hole. Since the scaling factor for distance is 30, the hole depth would be 30×6 ft $= 180$ ft. In this case there is a down-going direct impulse followed by a secondary reversed impulse caused by reflection from the base of the weathered layer or the top of the ground as shown in Figure 24. This situation occurs often in field practice—probably much more often than is generally suspected.

A Regular Layer System: Double Shot Impulse

The double shot impulse generated by the arrangement of Figure 23 will be applied to the regular layer system of Figure 21. The results are shown in Figure 25 and are at first surprising. When $L = 100$ feet, use of the doublet impulse causes strong cancellation of the reflections. As the distance L decreases, the reflection amplitude goes through resonance first near $L = 75$ feet and next near $L = 40$ feet. When L becomes still smaller, there is again strong cancellation of the reflections. These results can be explained by considering the fact that the two shot impulses are of opposite polarity and have a time separation of

$$\Delta t = \frac{2 \times 180 \text{ feet}}{10{,}000 \text{ ft/sec}} = .036 \text{ sec.}$$

For example, if the first reflection record of Figure 22 is delayed in time by .036 seconds, reversed in polarity, and then added to itself, the result will be the strong cancellation shown by the first reflection record of Figure 25.

CONCLUSION

This has been an argument by analogy. The acoustic model shown in Figure 26 has been connected to a standard set of seismic instruments and used to produce a variety of reflection records. These records have been used to advance the argument that each reflection seen on a seismic record is nearly always a composite of several reflections. In seismic exploration, a constant source of error is the naive idea that each line-up on the record represents a single interface which is to be plotted on the cross-section at a definite depth. There is the companion idea that each line-up on the seismic record is to be correlated with some single sharp kick on the well resistivity log. It was to dispel these ideas that the experiments were made with the acoustic model. The records made with the model have been discussed as if they were really seismic records even though correspondence between the acoustic model and the seismic earth is not exact. It must be remembered that the object has not been to develop and use some model as a sort of analog computer to prove that certain things happen when a seismic record is made under certain circumstances. There are seismic records taken in the field which show some of the same phenomena which are to be seen in the records from the model. These seismic records have not been presented

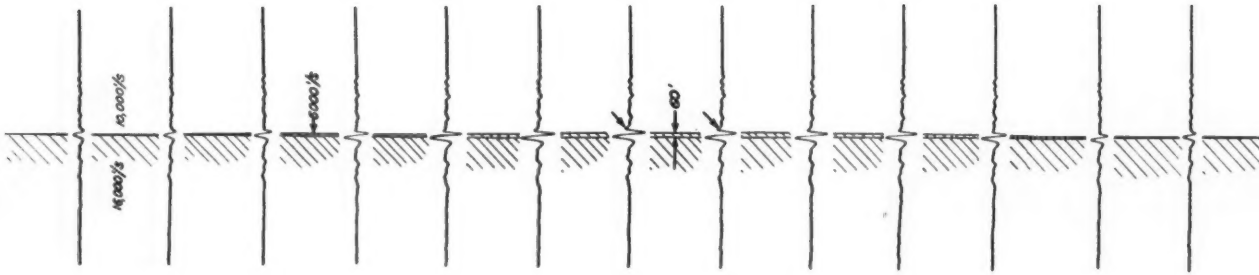


FIG. 14. Sand bar lying on limestone.

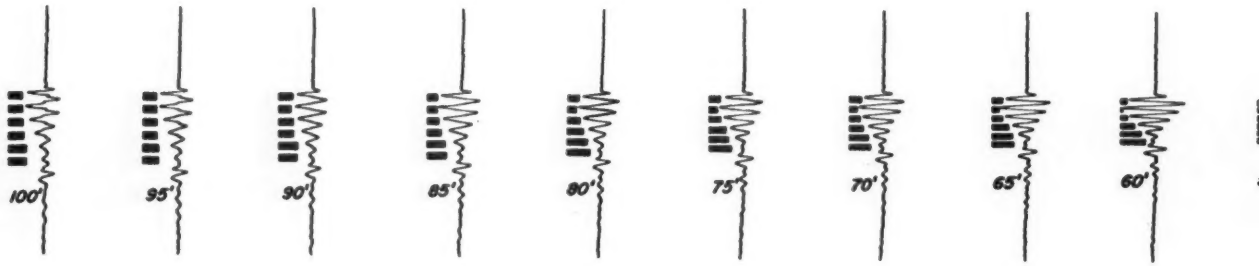


FIG. 22. Reflections from a regular layer system.

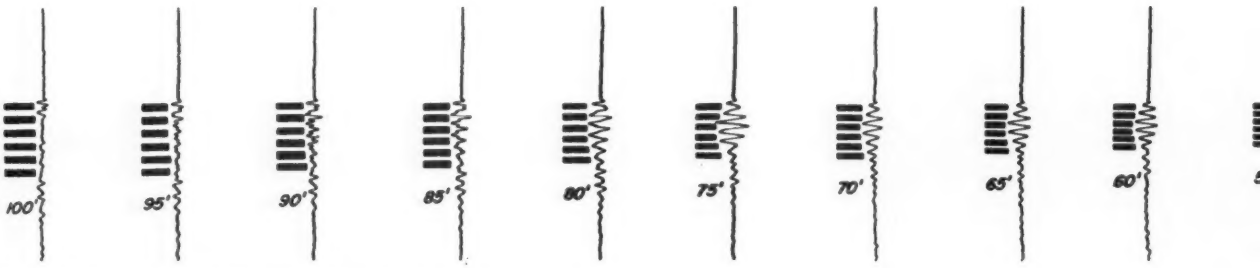


FIG. 25. Reflections from a regular layer system; double impulse from shot.

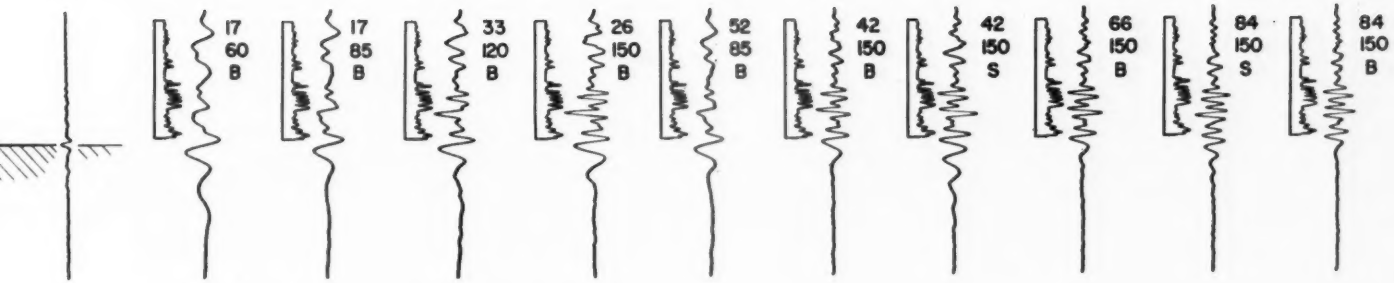
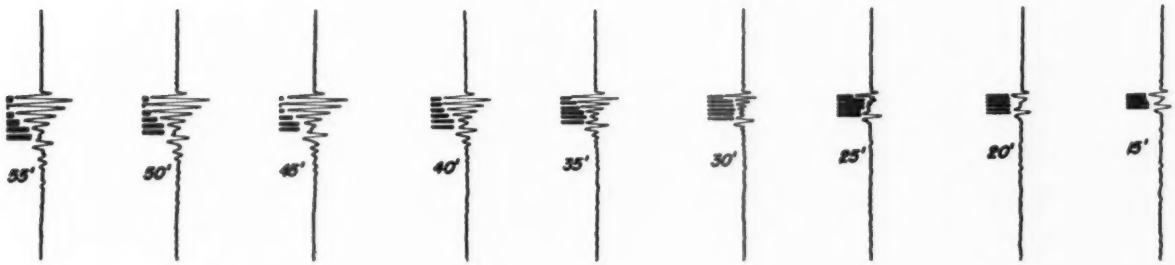


FIG. 16. Logs and reflections showing effect of filter variation.



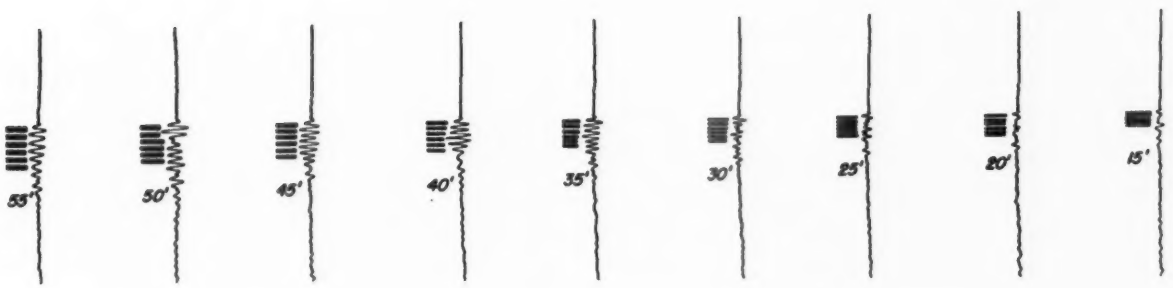


FIG. 26. Photograph of pipe and transducers.

because it is difficult to present seismic records in print and because any demonstration of an idea by actual seismic records is usually a complicated demonstration.

The records from the acoustic model present in a simple way the argument that reflections from closely spaced interfaces will interfere with each other to give a composite reflection. These records prove nothing about the earth. They are intended to create the suspicion that sometimes, in some areas, some seismic reflections may behave something like some of the reflections produced by the model.

GEOPHYSICS, VOL. XXI, NO. 2 (APRIL, 1956), PP. 277–284, 2 FIGS.

VARIATION OF ELASTIC WAVE VELOCITIES IN GRANITES WITH PRESSURE AND TEMPERATURE*

D. S. HUGHES† AND CHRISTIAN MAURETTE‡

ABSTRACT

The dilatational and rotational wave velocities have been measured as functions of pressure and temperature for five granites. The pressure range was 200–5,000 bars or higher. Dilatational velocities were measured over the temperature range 20–300°C.; rotational wave velocities over the range 20–200°C. These data indicate that below fairly shallow depths in the granitic layer the velocity is constant or even slightly decreasing.

INTRODUCTION

Laboratory measurements of elastic wave velocities in rocks under controlled pressure and temperatures should be helpful in solving general problems relating to physical conditions within the earth's crust. Professor Francis Birch has developed a method of measuring rotational or shear velocities that can be used at pressures of several thousand bars and temperatures up to 600°C. (Birch, 1937; Birch and Bancroft, 1938; Birch, 1943).

A method of measuring the dilatational or longitudinal wave velocity under high pressures and temperatures up to 300°C. has also been developed (Hughes and Jones, 1950; Hughes and Jones, 1951; Hughes and Cross, 1951). The temperature range of this method can be extended. Under some conditions it also gives the rotational wave velocity. This point will be discussed later.

Since granite is a most important constituent of the outer crust, it was decided to limit the present work to granites. Five were selected, the Quincy, Westerly, and Woodbury of New England, and the Texas Gray and Texas Pink.

APPARATUS AND METHODS

The apparatus is quite similar to that described by Hughes and Cross (1951). The pressure apparatus has been modified by adding a second intensifier that permits maximum pressure of 10,000 bars (145,000 psi) to be reached. A new pressure cylinder has been constructed with an internal furnace which permits much faster heating and cooling and also should permit a much higher temperature to be reached. The pressure apparatus has also been modified so that argon, carbon dioxide, or kerosene can be used as the transmitting fluid.

The electronic apparatus is identical with that of the above reference. The method used here consists of applying a pulse to a driving crystal on one end of

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the sample and measuring the time required for the pulse to strike a second crystal on the opposite end of the sample. In measuring the properties of rocks under pressure it is necessary to exclude the pressure fluid from the pore space of the rock (Adams and Williamson, 1923; Birch and Bancroft, 1938). We have used two types of jackets. Figure 1 shows the jacket used with x-cut crystals. A close fitting copper tube is pushed over the sample and spun copper caps pushed into into the ends. This construction permits soldering the caps in place without excessive heating of the sample. The crystals are placed in the end caps and held in place by a light spring pressure. When kerosene is used as a pressure fluid, it gives

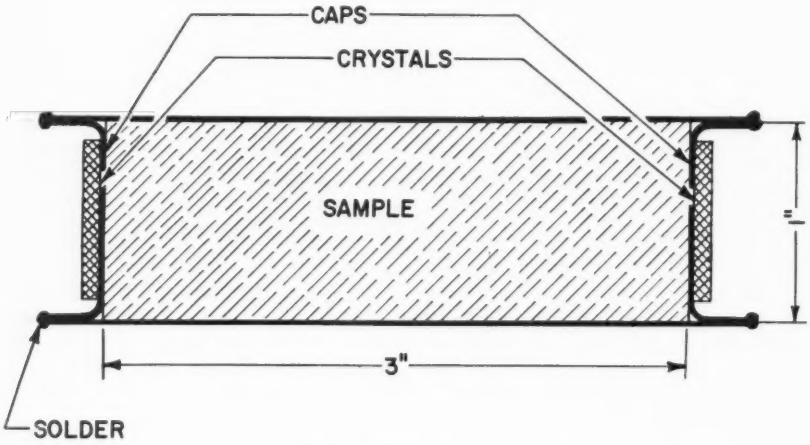

FIG. 1. Sample mounting for X-cut crystals.

excellent acoustic coupling of the sample to the crystal. With carbon dioxide or argon no coupling is obtained until the pressure is raised to a few hundred bars. This jacket can not be used conveniently with shear crystals. By using rosin or wax, coupling can be secured at low temperatures, but with any increase in temperature it softens and the signal is lost.

The second type of jacket, Figure 2, was designed to remove this difficulty. Here the crystals are placed inside the jacket and are seated by the full hydrostatic pressure. Either x or y-cut crystals can be used, and very excellent acoustic coupling is obtained. This jacket suffers from the defect that it can not be used above 200° C. It usually lasts for a run of 200°C. but leaks after cooling down. We plan to try Teflon O-rings which should permit a higher temperature.

When a sharp dilatational pulse is sent down a cylinderical rod, it is found that at the receiving crystal the first pulse which travels with the dilatational wave velocity is followed by a series of delayed pulses (Hughes, Pondrom, and Mims, 1949). The arrival time of these pulses should be a simple function of the

diameter of the rod, the dilatational wave velocity, and the rotational wave velocity. For metals and many rocks the rotational wave velocity measured in this way is quite accurate. Our results on the Quincy Granite (Hughes and Cross, 1951) was about 10 percent lower than Professor Birch's value, although our value on the Solenhofen limestone, Cheshire quartzite, and marble checked very well.

By using y-cut crystals and the jackets of Figure 2, we have compared the rotational velocities obtained by using the delayed or transformed pulses and those obtained by using shear pulses. It now appears that with homogeneous materials, metals, and quartzite, the two methods agree perfectly. With coarse

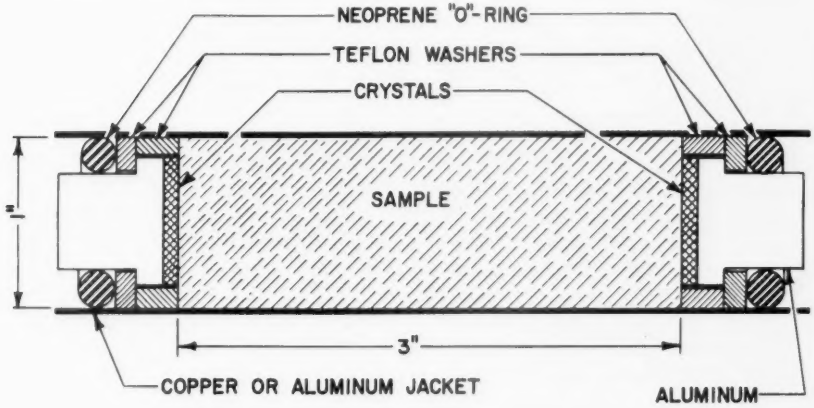

FIG. 2. Sample mounting for Y-cut crystals.

grained rocks there may be serious errors in using the transformed pulse. This error arises apparently from the destruction of the initial part of the pulse by interference and reflection at the grain boundaries.

The rotational velocities and Poisson's ratio for the Quincy granite and probably the Barriefield granite as given in Hughes and Cross (1951) are incorrect. The values of these quantities for the Norite and Diorite in Hughes and Jones (1950) are also proably in error.

RESULTS

After consultations with Professor Clabaugh and Muehlberger of the Geology Department of the University, three granites were selected as being typical of large granite masses. These were the Texas Gray, Texas Pink, and the Woodbury of Vermont. In addition we have also made some measurements on the Quincy and Westerly granites for comparison.

Professor Clabaugh gave us the following descriptions from an examination of thin sections.

Medium-grained pink granite, Llano County, Texas

The principal minerals are quartz, microcline, Biotite and plagioclase (andesine-oligoclase). The minor accessory minerals are zircon, sphene, apatite, and magnetite and ilmenite. Secondary minerals produced by deuteric alteration are sercite, calcite, chlorite and fluorite.

The average grain diameter is slightly less than 5 mm although a few feldspar crystals are more than 1 cm long. The rock is essentially equigranular, but its texture approaches porphyritic because of the few larger feldspar crystals. Most of the crystals of the major constituents are irregular; sphene occurs in euhedral crystals as much as 2 or 3 mm long, and apatite and zircon in minute prisms. Quartz makes up about 25 percent of the rock, and the remainder is chiefly feldspar, with microcline more abundant than plagioclase. Plagioclase is sufficiently abundant that the rock approaches quartz monzonite in composition. The quartz is chiefly in clear, large crystals with very slight undulatory extinction. The microcline crystals are very slightly perthitic, having very small irregular patches of plagioclase in them. Both the microcline and the plagioclase are clouded with irregular patches of sercite and a clay mineral (?), and the alteration is more severe in the cores of the zoned plagioclase crystals, some of which appear to be largely replaced by secondary minerals. Minute calcite patches accompany the sericite; but the amount of secondary calcite is exceedingly small. Most of the larger crystals of biotite are fresh, but the smaller ones are partly replaced by chlorite. Traces of fluorite are present along grain boundaries at a few places. The rock has evidently undergone a moderate amount of deuteric alteration and weathering as well.

Biotite granite, Woodbury, Vermont

The principal minerals are microcline, quartz, biotite, plagioclase (oligoclase), and muscovite. The minor accessory minerals consist of very small quantities of zircon, apatite, sphene, magnetite and ilmenite. The secondary minerals produced by deuteric alteration (and weathering?) are chlorite, calcite, and sericite.

Average grain diameter is between 1 and 2 mm; the rock is nonporphyritic, more or less equigranular. Plagioclase and biotite crystals are subhedral, most of the other major constituents are present in anhedral crystals. The minor accessory minerals are in minute euhedral crystals. About 40 percent or more of the rock is quartz which shows evidence of deformation in undulatory extinction and lines of bubbles along incipient fractures. Microcline is next most abundant, making up about 20 to 30 percent of the rock. Most of it is fresh and unaltered except for mariinal replacement of a few grains by plagioclase. The plagioclase (oligoclase) is zoned and altered, with numerous ragged muscovite flakes, irregular patches of calcite, fine flakes of sericite and cloudy patches of clay minerals (?). Alteration products have replaced as much as 5 to 10 percent of some of the plagioclase crystals. Some of the biotite flakes are partly replaced by chlorite;

others are unaltered. The rock appears to have been deformed slightly and subjected to deuteric alteration late in its cooling history, or to have been acted upon by hydrothermal solutions, but not severely altered.

Fine-grained gray granite, Llano County, Texas

The principal minerals are quartz, microcline, biotite, and plagioclase (oligoclase). Minor accessory minerals (very small quantities of each) are zircon, apatite, magnetite and ilmenite. Secondary minerals produced by deuteric alteration and weathering are muscovite and sericite, chlorite, and epidote.

The average grain diameter is between $\frac{1}{2}$ and 1 mm; the rock is essentially equigranular. Most of the minerals are anhedral, with biotite and plagioclase tending to occur as subhedral crystals slightly smaller than the average grain size. Quartz makes up 25 percent or less of the rock, occurring both as larger clear grains and as swarms of small round blebs in microcline in a peculiar graphic intergrowth. The quartz shows slight undulatory extinction and a few lines of bubbles along incipient fractures. Quartz and sodic plagioclase occur together in a few patches of myrmekite replacing edges of microcline crystals. Microcline makes up more than half of the rock and zoned plagioclase crystals compose less than 25 percent of it. The microcline crystals are very irregular, interlocking with adjacent microcline and quartz grains. Both the microcline and plagioclase are clouded by irregular patches of a clay mineral (?), but the plagioclase is more strongly altered than the microcline, most of which appears fresh. The plagioclase is zoned, and the cores more clouded than the rims and partly replaced by sericite. A few irregular crystals of muscovite occur with the biotite and partly replace plagioclase crystals. Most of the biotite is fresh, but a few grains are partly or wholly replaced by dark green chlorite. The rock appears to have undergone normal deuteric alteration during the late stages of its cooling and possibly to have suffered a slight amount of weathering.

The results are presented in Tables I–V. From Table I it appears that V_R in the Quincy measured with shear crystals checks very closely with Professor

TABLE I

QUINCY GRANITE
Velocities in km/sec. Density: 2.629 gr/cm³

	25°C.		100°C.	30°C.
P bars	V_D	V_R	V_D	V_R (Birch 1942)
200.	5.92	3.34		
500	6.06	3.43	5.56	3.44–3.47
1,000	6.21	3.44	5.88	
1,500	6.26	3.45	6.07	
2,000	6.30	3.46	6.12	
3,000	6.34	3.47	6.22	
4,000	6.38	3.48	6.34	3.59–3.62
5,000	6.40	3.50	6.40	

TABLE II

WESTERLY GRANITE
Velocities in km/sec. Density: 2.615 gr/cm³

	25°C.		100°C.	30°C.
P bars	V_D	V_R	V_D	V_R (Birch 1944)
200	5.90	3.50		
500	5.98	3.52	5.89	3.27
1,000	6.06	3.55	6.03	
1,500	6.09	3.56	6.07	
2,000	6.12	3.57	6.11	
3,000	6.14	3.58	6.15	
4,000	6.18	3.59	6.18	
5,000	6.22	3.59	6.21	

Birch's value (Birch, 1942). However, our value on the Westerly is about 7 percent higher. This difference appears somewhat large to be simply due to sample differences. This granite we have found to be extremely sensitive to temperature. Heating to even 150°C. at atmospheric pressure results in a large permanent decrease in velocity (Ide, 1937). This was one reason for the jacket design shown in Figure 1. We have made it a rule in this work never to lower the pressure below 200 bars with the sample heated to 100°C. or below 500 bars at the higher temperatures. It appears that this practice reduces some of the changes with heating that have been observed.

It is, of course, questionable whether or not in a laboratory experiment, in which the rock is raised from atmospheric pressure and room temperature to a pressure of 5,000 bars and a temperature of 300° in the course of a few hours, if the rock is actually in the same state as in earth's crust at this same pressure and temperature. We have found that leaving the sample at the highest pressure and temperature for periods up to 48 hours makes no detectable difference.

At 500 bars the change in velocity with temperature is very small for the 25–100°C. range for all samples except the Quincy; above 100°C. the velocity decreases rather rapidly with temperature. At 5,000 bars the variation with tem-

TABLE III

WOODBURY BIOTITE GRANITE
Velocities in km/sec. Density: 2.634 gr/cm³

	25°C.		100°C.		200°C.		300°C.
P bars	V_D	V_R	V_D	V_R	V_D	V_R	V_D
200	5.77	3.31					
500	6.05	3.46	6.04	3.41	6.00		5.77
1,000	6.16	3.56	6.13	3.54	6.06	3.45	5.87
1,500	6.20	3.61	6.18	3.58	6.13	3.55	5.92
2,000	6.22	3.63	6.21	3.61	6.15	3.60	5.95
3,000	6.26	3.66	6.22	3.64	6.18	3.62	6.01
4,000	6.29	3.67	6.26	3.66	6.20	3.63	6.04
5,000	6.31	3.68	6.29	3.68	6.22	3.65	6.08

TABLE IV

TEXAS PINK GRANITE
Velocities in km/sec. Density: 2.636 gr/cm³

	25°C.		100°C.		200°C.		300°C.
P bars	V_D	V_R	V_D	V_R	V_D	V_R	V_D
200	6.14	3.27	6.01	3.16			
500	6.29	3.35	6.23	3.28	5.86	3.13	5.57
1,000	6.34	3.35	6.32	3.32	6.17	3.26	5.94
1,500	6.41	3.38	6.35	3.33	6.26	3.31	6.07
2,000	6.43	3.39	6.38	3.34	6.30	3.32	6.12
3,000	6.47	3.38	6.42	3.35	6.35	3.34	6.18
4,000	6.50	3.36	6.47	3.36	6.38	3.35	6.25
5,000	6.52	3.37	6.49	3.36	6.42	3.36	6.33
6,000	6.54	3.39	6.52	3.36	6.46	3.36	6.37
7,000	6.56	3.39	6.53	3.37	6.49	3.36	6.43

perature is much less, but the same pattern is evident. The change with temperature is very small in the range 25–100°C. but increases above 100°C. except for the Texas Gray, Table V; here the velocity is almost linear with temperature.

In Table VI we have computed the velocities and Poisson's ratios to be expected at various depths in granite for Texas Pink and Gray and the Woodbury. Poisson's ratio for the Quincy and Westerly at 2 km is included for comparison.

A temperature gradient of 24°C. per km has been used. This value was based upon a heat flow of 1.448×10^{-6} cal. per cm², per sec (Birch, 1942, page 269) and a conductivity of 6.0×10^{-3} cal per cm, per sec, per degree Centigrade (Birch, 1942, page 251). This value of the conductivity was measured at atmospheric pressure and room temperature. The conductivity increases with pressure and decreases with temperature, thus these two factors to some extent counteract each other.

From Table VI it appears that the seismic velocities in granite should vary

TABLE V

TEXAS GRAY GRANITE
Velocities in km/sec. Density: 2.609 gr/cm³

	25°C.		100°C.		200°C.		300°C.
P bars	V_D	V_R	V_D	V_R	V_D	V_R	V_D
200	5.78	3.42					
500	5.96	3.55	5.94	3.54	5.80	3.41	5.27
1,000	6.10	3.58	6.02	3.57	5.89	3.55	5.53
1,500	6.15	3.59	6.08	3.58	5.96	3.55	5.67
2,000	6.19	3.59	6.11	3.59	6.00	3.57	5.75
3,000	6.23	3.60	6.15	3.59	6.06	3.58	5.90
4,000	6.25	3.61	6.18	3.60	6.14	3.59	6.00
5,000	6.28	3.61	6.22	3.60	6.14	3.59	6.08
6,000	6.30	3.61	6.24	3.60	6.18	3.59	6.10
7,000	6.32	3.62	6.27	3.61			6.15
8,000	6.34	3.62					6.18

TABLE VI

Depth (km)	1	2	5	10
Press. (bars)	260	520	1,300	2,600
Temp. (°C.)	40	64	136	256
QUINCY σ (25°)		.264		
WESTERLY σ (25°)		.235		
Woodbury V_D		6.04	6.13	6.14
V_R		3.44	3.54	(3.59)
σ		.260	.250	.240
TEXAS PINK V_D	6.14	6.26	6.30	6.23
V_R	3.22	3.31	3.31	(3.32)
σ	.310	.305	.309	.301
TEXAS GRAY V_D		5.95	6.01	5.93
V_R		3.54	3.56	3.56
σ		.228	.230	.218

only slightly with depth and that the maximum possible velocity in granite is about 6.25 km/sec. The temperature gradient used is believed to be about the minimum possible; a larger gradient would cause substantial decrease in velocity.

The authors wish to express their gratitude to Professor Clabaugh for his study of the thin sections.

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GEOPHYSICS, VOL. XXI, NO. 2 (APRIL, 1956), PP. 285–298, 7 FIGS.

SEISMIC WAVE STUDIES OVER A HIGH-SPEED SURFACE LAYER*

FRANK PRESS† AND MILTON B. DOBRIN‡

ABSTRACT

The propagation of compressional, shear, and surface waves was studied along a 3,200 ft profile at a location where a 95-ft-thick surface layer of Austin chalk, with a compressional velocity of about 9,900 ft/sec, overlies a 400-ft section of Eagle Ford shale with a speed of about 6,500 ft/sec. Woodbine sand, with a velocity of about 9,900 ft/sec, underlies the shale.

Refracted first arrivals transmitted through the high speed surface layer show an increase of frequency with distance from the shot. A refracted second arrival from the Woodbine decreases in frequency and, after correction for spreading, increases in relative amplitude with distance. This would indicate that the high-speed surface layer acts as a high-pass filter for energy transmitted horizontally and as a low-pass filter for energy transmitted vertically through the layer. Shear waves transmitted through the Austin chalk are also observed.

Surface waves consist of two groups of arrivals; a brief train of high-frequency waves (greater than 20 cps) propagated almost entirely in the surface layer is followed by a short train of low frequency waves. Unlike surface waves in most other localities, the two groups show almost no dispersion. The characteristics of both kinds of waves are interpreted qualitatively in terms of the layering.

INTRODUCTION

In a large majority of the areas where seismic prospecting is carried on, the material at the surface has a lower velocity than any deeper formations. Most often this low-speed material occurs as an unconsolidated, or weathered, layer which extends downward to a discontinuity tens of feet deep. Below this discontinuity, the rocks become more consolidated and the velocity increases substantially.

Occasionally, however, the layer at, or very near, the surface has a higher velocity than the formations below it. Where this occurs, one would expect the near-surface wave propagation to have unique characteristics which are not encountered with the more usual type of layering.

The Magnolia Petroleum Company's Field Research Laboratories in Dallas County, Texas are located in an area where the formation at the surface (excluding a superficial weathered zone) has a higher velocity than the material it overlies. This formation, the Austin chalk, is 95 ft thick here. Below it is the Eagle Ford shale formation, about 400 ft thick, which overlies the Woodbine sand. The Austin chalk has, below a 15-ft layer of soil and weathered rock, an average compressional speed of about 9,900 ft/sec, whereas the underlying Eagle Ford has an average speed of 6,500 ft/sec. This location is therefore particularly suitable for

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experiments on seismic wave propagation in the presence of a high-velocity surface layer.

A series of such experiments was conducted during the spring of 1950 by the experimental seismic crew of the Magnolia Field Research Laboratories. A 3,200-ft profile was laid out along a road adjoining the Laboratories grounds. The spacing of geophones was chosen to permit identification of all waves, both body and surface, traveling through the near-surface layers.

These experiments showed several types of traveling waves which might interfere with reflections received over a high-speed surface layer. Both body waves and surface waves tend to have frequencies in the same range as reflection frequencies. The characteristics of the various wave types will be explained on the basis of wave theory.

ELASTIC LAYERING

The distribution of near-surface velocities, both compressional and shear, as measured in a shallow borehole 800 ft east of the experimental profile, is shown in Figure 1. The interface between the high-speed Austin chalk and the lower-velocity Eagle Ford shale below it is clearly indicated at about 95 ft. Another discontinuity in speed at about 15 ft suggests the presence of a low-speed layer in the Austin chalk just below its top surface. Examination of core samples very near the hole where the log was made leads to the conclusion that this layer is intrinsically a soft component of the chalk and is not a zone of weathering. The regional dip is such that this low-speed Austin should be either much thinner or missing at the present shot point.

The velocities shown in Figure 1 were determined with techniques of the type described by White and Sengbush (1953). The anisotropy, observable on the logs, in the compressional and shear velocities of the chalk and shale is discussed in their paper and related to theory.

A superficial soil layer about two or three feet thick overlies the Austin, but its seismic velocity was not obtainable with the type of apparatus used in the up-hole survey.

EXPERIMENTAL SETUP

The recording system employed in this study gave a flat frequency response from 5 to 200 cps. Vertical geophones were placed every 50 ft and horizontal geophones (oriented along and normal to the profile) every 450 ft, so that the first three traces of each 450-ft geophone spread showed the three components of ground motion. Seven spreads of this type, covering a shot-geophone distance range of 3,200 ft, were shot from the bottom of a hole 50 ft deep and one geophone spread (extending from 1,380–1,830 ft) from a 100-ft shot hole. A single air shot, from a stake 8 ft high, was also recorded by the 1,380–1,830-ft geophone spread.

Figure 2 shows the record array obtained from the 50-ft shots. Figure 3*a*

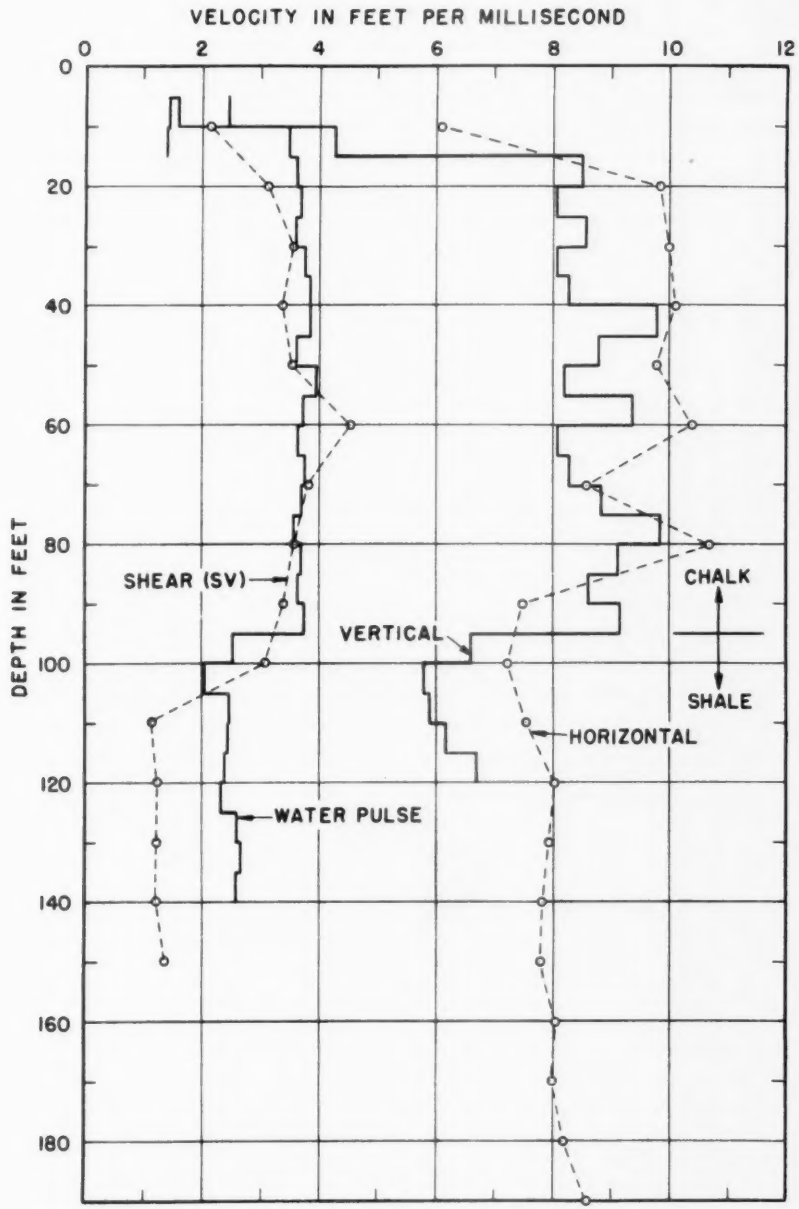

FIG. 1. Velocity logs showing variation of interval velocities with depth in borehole on Magnolia Laboratories grounds, Dallas County, Texas. (Reproduced from paper by White and Sengbush published in January, 1953 GEOPHYSICS.)

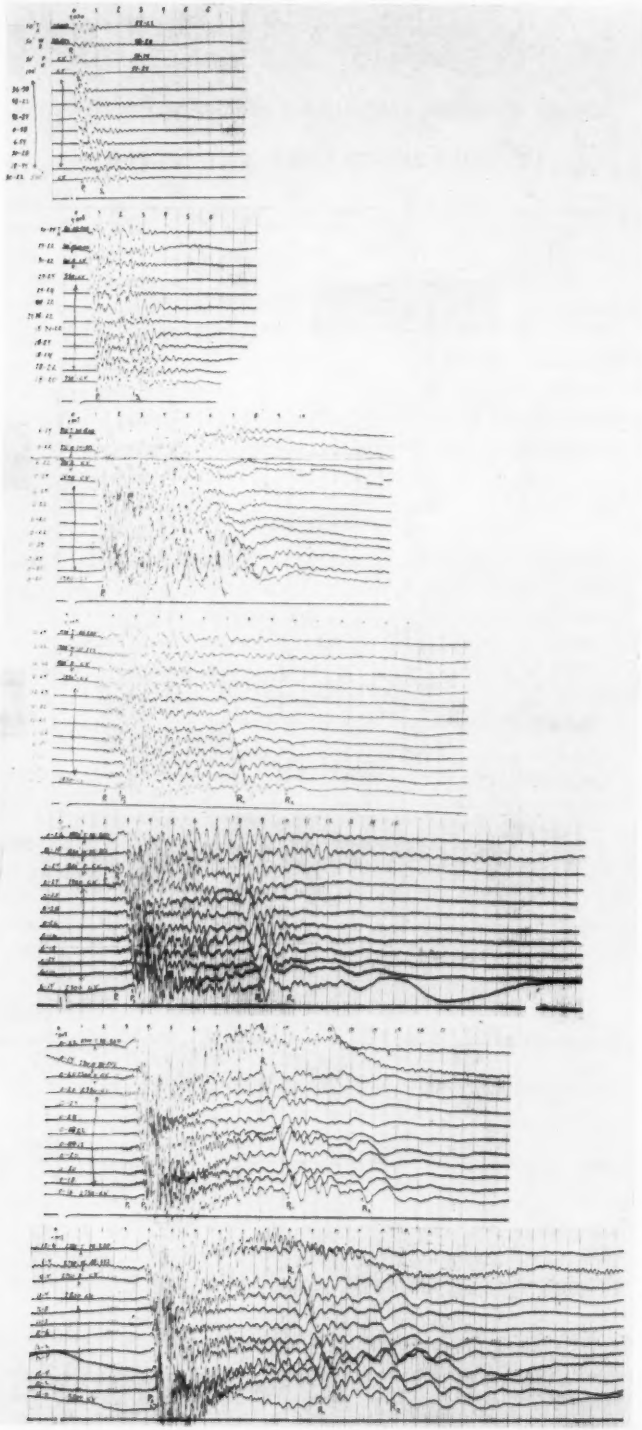

FIG. 2. Array of records showing wave propagation from 50 to 3,200 ft on profile over high-speed surface layer adjacent to Magnolia Laboratories grounds, Dallas County, Texas. Shot depth is 50 ft. Spacing of vertical geophones is 50 ft. First two traces of each record are from horizontal geophones oriented, respectively, along and perpendicular to profile.

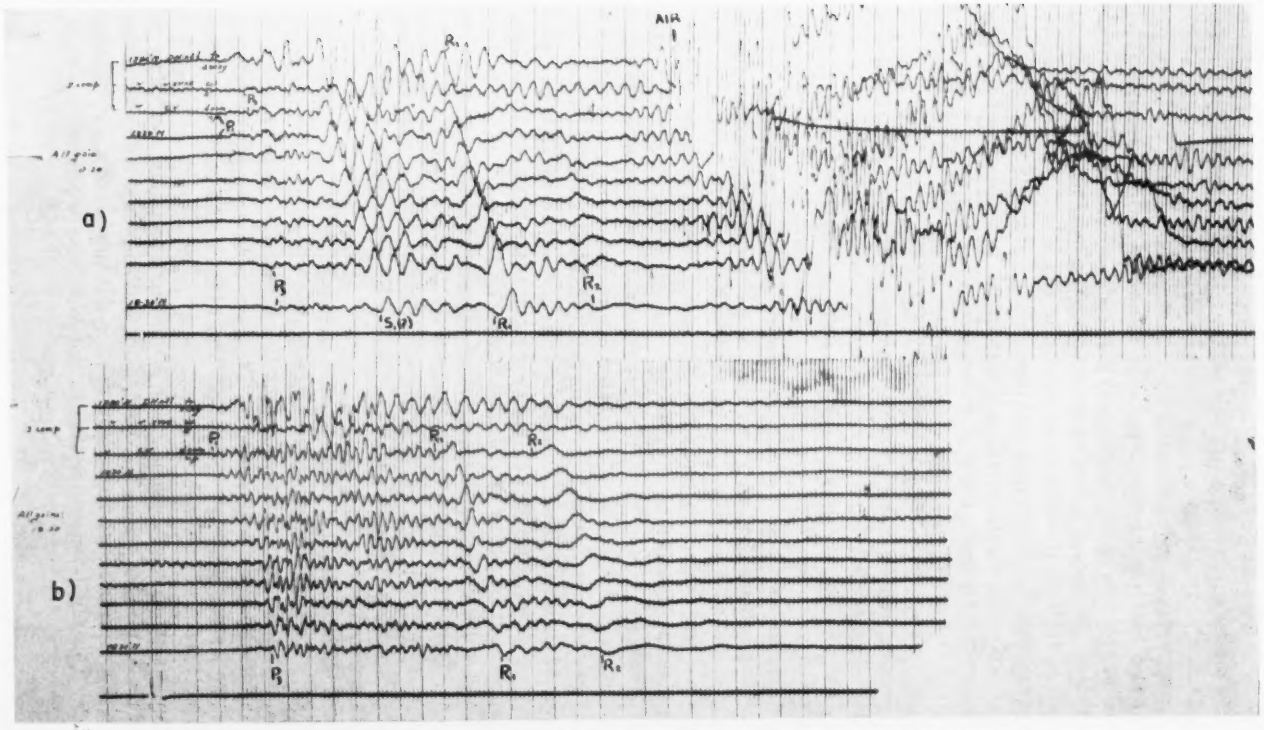

FIG. 3*a*. Record from a single air shot received at 50 ft intervals in range 1,380–1,830 ft from shot.
First two traces show horizontal ground motion, remainder show vertical.
FIG. 3*b*. Record from hole shot 100 ft deep recorded with same geophone spread.

shows the record from the single air shot and Figure 3*b* shows the record obtained at the same distance from the 100-ft hole shot.

Several discrete types of traveling waves were observed on the records. These included compressional waves traveling directly through the high-speed Austin chalk and also through the Woodbine sand below the low-speed Eagle Ford formation; shear waves in the Austin; and Rayleigh waves. Figure 4 is a time-distance plot of the various traveling events. The segments marked P_1 and P_3 (corresponding to similarly designated phases on the records) are believed to represent compressional waves refracted from the Austin and Woodbine formations respectively. The segment marked S_1 corresponds to shear arrivals, and the R_1 and R_3 segments represent Rayleigh waves.

REFRACTED COMPRESSIONAL WAVES

The refracted first arrivals (P_1) exhibit a very curious behavior (Figures 2 and 5). For short shot-detector distances these waves are predominantly low frequency (80–120 cps). As the shot-detector distance increases, the amplitude diminishes and, contrary to normal behavior, the wave frequency increases to about 400 cps, possibly higher, since this represents the high frequency cut-off of the recording system. The first arrivals plot on a straight line giving a velocity of 9,900 ft/sec and an intercept of .013 second (Figure 4).

All of these features are characteristic of a compressional wave transmitted through a high-speed surface layer overlying a thicker low speed section. It can be shown (Press and Ewing, 1948) that compressional waves propagated horizontally through such a layer are attenuated due to leakage of energy into the underlying low velocity material, the magnitude of the attenuation decreasing with increasing frequency. Thus, an impulse transmitted horizontally loses low-frequency more rapidly than high-frequency components, resulting in an increase of the predominant frequency of the pulse with shot-detector distance. In this manner a high-speed surface layer acts as a high-pass filter for energy transmitted horizontally. The agreement of velocity with borehole data (Figure 1) and the small value of the travel-time curve intercept further verify the interpretation of the first arrival as a compressional wave transmitted horizontally through the high-speed surface layer.

As the surface-transmitted compressional wave diminishes, a second arrival appears (P_3). This has a much higher amplitude than the P_1 arrival at the same distance and at distances greater than 1,500 ft it becomes the most outstanding event in the early part of the seismogram. The travel time curve gives a velocity of 9,900 ft/sec and an intercept of .096 sec. This event is interpreted as a compressional wave refracted through the Woodbine.

Several interesting questions are raised by this interpretation. According to the usual geometric-path theory it should be impossible to observe a Woodbine refraction at a finite distance with a shot point in the Austin and a geophone on the surface. This follows since the Austin and Woodbine represent two high-

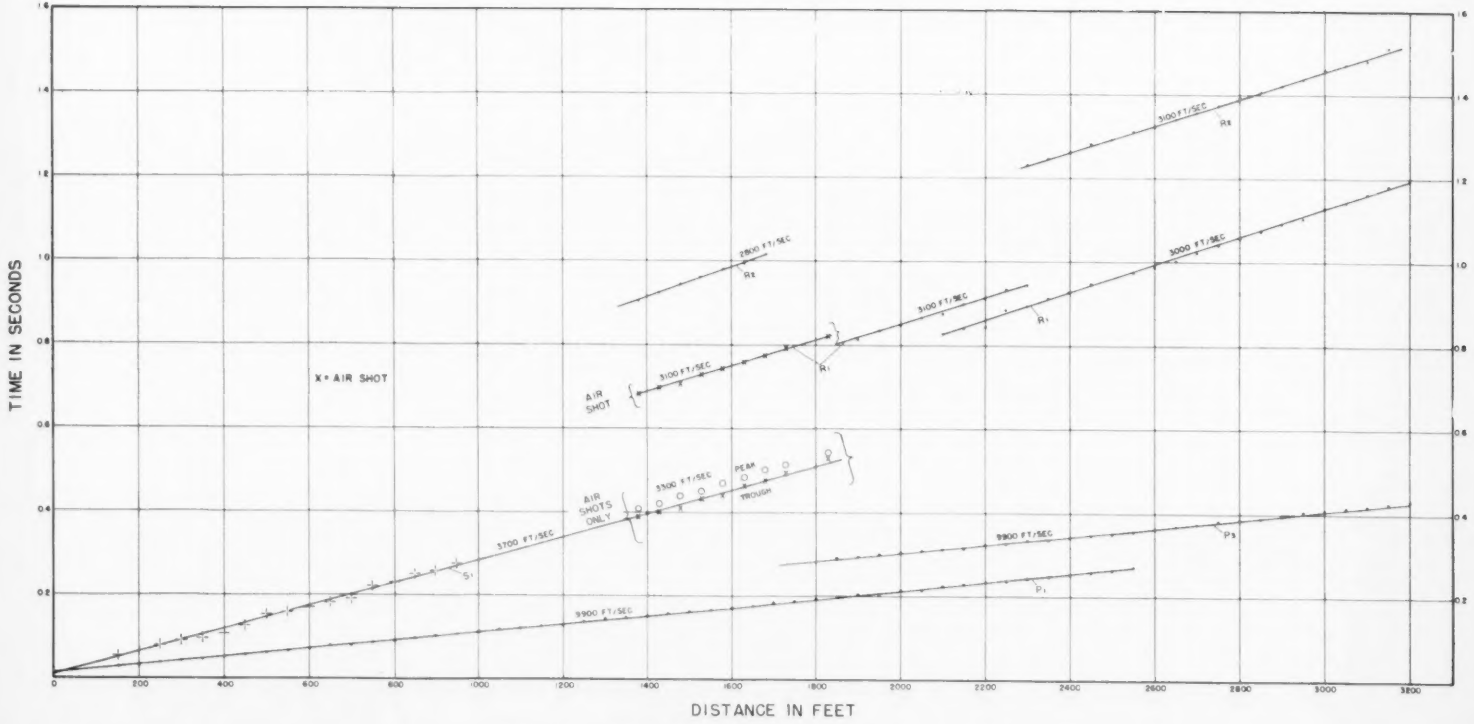

FIG. 4. Time-distance plot for records of Figures 2 and 3*a*.

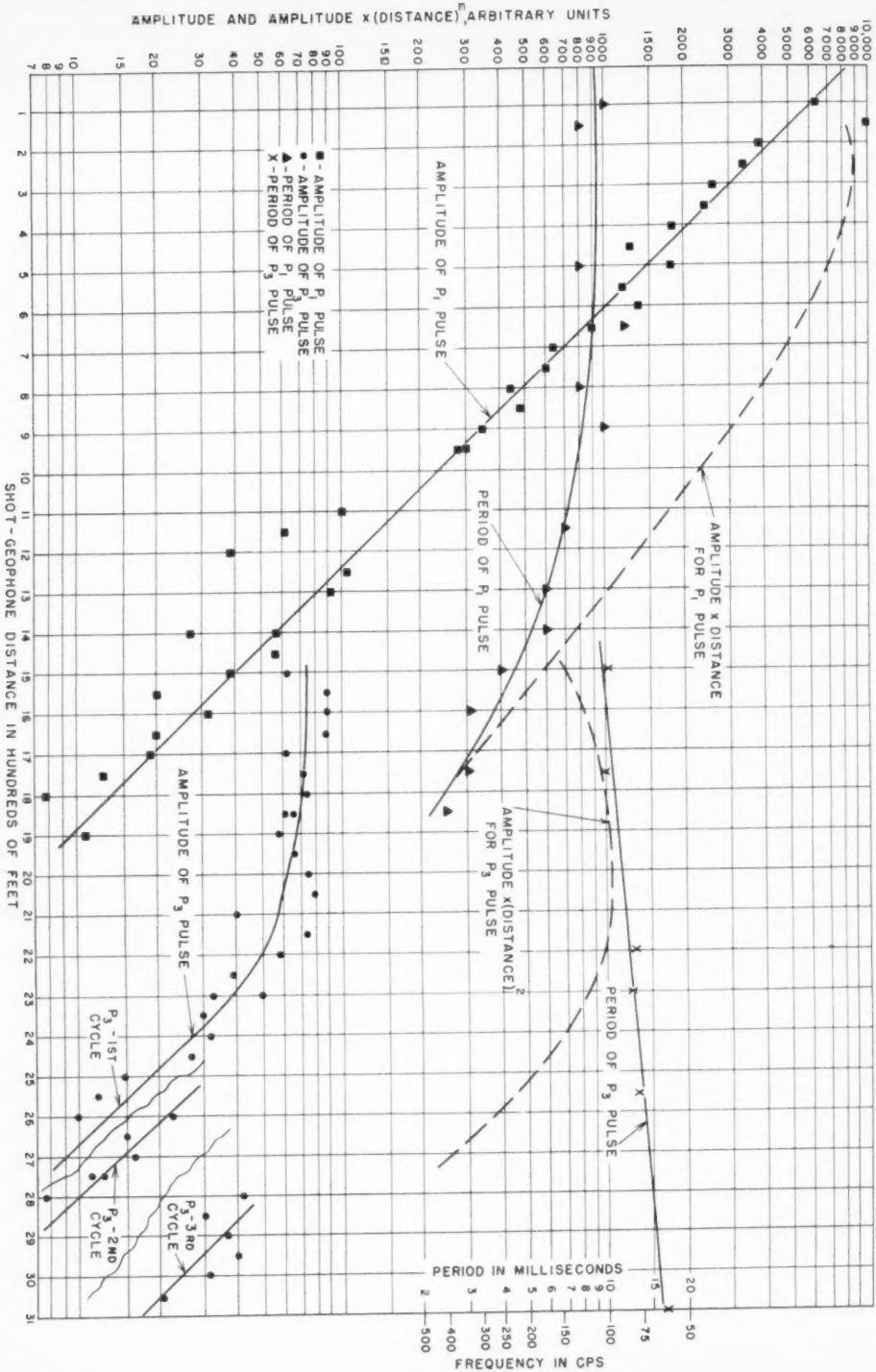
AMPLITUDE AND AMPLITUDE x (DISTANCE)n, ARBITRARY UNITS
■ - AMPLITUDE OF P1 PULSE
● - AMPLITUDE OF P3 PULSE
▲ - PERIOD OF P1 PULSE
X - PERIOD OF P3 PULSE
AMPLITUDE OF P1 PULSE
PERIOD OF P1 PULSE
AMPLITUDE x DISTANCE FOR P1 PULSE
AMPLITUDE x (DISTANCE)2 FOR P3 PULSE
AMPLITUDE OF P3 PULSE
PERIOD OF P3 PULSE
P3 - 1ST CYCLE
P3 - 2ND CYCLE
P3 - 3RD CYCLE
SHOT - GEOPHONE DISTANCE IN HUNDREDS OF FEET
PERIOD IN MILLISECONDS
FREQUENCY IN CPS

FIG. 5. Amplitudes and periods of P_1 and P_3 arrivals as functions of distance from shot.

speed layers having almost identical horizontal velocity (9,900 ft/sec) separated by a relatively thick section of lower-speed Eagle Ford. Geometric-path theory, however, fails to apply for wavelengths of the order of the thickness of the Austin or larger ($L \geqq 100$ ft) so that a Woodbine refraction could be observed for frequencies under 100 cps. As the shot-detector distance becomes large compared to the thickness of the Austin, conditions permitting geometric paths are approached and one should find greater prolongation and increased relative amplitudes in the Woodbine refractions. These characteristics are observed on the seismograms of Figure 2. Figure 5 shows that the frequency of the P_3 arrival decreases slightly with increasing distance from the shot. This is attributed to the normal selective attenuation of higher frequencies in earth materials. Initially, the amplitude of P_3 is almost constant with increasing distance. Allowing for the theoretical r^{-2} decrease in amplitude of refraction arrivals it is seen from Figure 5 that the constant initial amplitude actually corresponds to more efficient excitation of P_3 as distance increases.

These features of the Woodbine refractions illustrate the manner in which a high-speed surface layer can act as a low-pass filter of energy transmitted downward. The filtering action of the high-speed layer is not necessarily limited to refractions, being applicable under certain conditions to reflections from deep layers. Experiments verifying the filtering effect of plates with other applications have been successfully performed (Osborne and Hart, 1948).

An interesting example of a contrast in frequency of a refracted wave for an air shot and a hole shot below the Austin is shown in Figure 3 for a spread of 1,380–1,830 ft. It is seen that the P_3 arrival from the air shot is predominantly 20 cps and the corresponding arrival for the hole shot is about 100 cps. Whether this phenomenon is due to differences in the source spectra of air and hole shots or to the filtering effects described above, or to a combination of both, cannot be established on the basis of these records.

The computed intercept of the Woodbine refraction (P_3) using the thickness and velocity of the Eagle Ford listed in a previous section is .102 sec. This figure is reasonably close to the observed value of .096 sec. The computation was based on the assumption of vertical ray paths through the Austin chalk.

In the preceding discussion such effects as frequency-selective absorption, influence of shot location, initial spectrum, etc., have not been considered although they certainly should influence record character. It is believed, however, that the major features of the first and second arrivals are explainable in terms of the influence of the high-speed surface layer.

DIRECT SHEAR WAVES

An event (S_1) which can be followed with some difficulty in the seismograms in the interval 150–950 ft is plotted as crosses in the time-distance curve (Figure 4). After 950 ft the arrival is lost in the prolonged activity associated with the Woodbine refraction. An approximate travel time curve can be fitted to the data

giving a velocity of 3,700 ft/sec and an intercept of .01 sec. This arrival is tentatively identified as a shear wave transmitted through the Austin Chalk. The velocity is in excellent agreement with the value of 3,700 ft/sec computed by use of a laboratory-determined chalk density of 2.2 gm/cm^3 and a rigidity of 2.9×10^{10} dynes/cm^2 determined in a borehole using the water-pulse-velocity technique.

A curious, large-amplitude disturbance consisting of several waves which have a frequency of 25 cps appears on the air-shot record (Figure 3*a*). This arrival plots on an extension of the shear wave curve and is further characterized by ground motion on all three components. It is present only on the horizontal geophones for the corresponding deep-hole shot. Although further work is necessary to establish the identity of this arrival and explain its large amplitude, we shall tentatively label it as a shear wave.

RAYLEIGH WAVES

The ground roll observed on this profile differs markedly from that found at other locations in that the surface waves show for the most part very little dispersion and are brief in duration. Two predominant groups, labeled R_1 and R_2 in Figures 2 and 3, are observed. For both groups, phase (step-out) velocity exceeds group (distance ÷ time) velocity as shown by the time-distance curves of Figure 4. The R_1 group begins as a large-amplitude, single-cycle pulse followed by several small oscillations of higher frequency. The R_2 group is best developed at the larger distances and is more readily excited by deeper shots (compare R_2/R_1 amplitude ratio for 100-ft shot, 50-ft shot, and surface shot at same shot-detector distance in Figures 2 and 3). R_2 occurs as a very low frequency oscillation, faintly exhibiting an incipient inverse dispersion in which the higher frequency components arrive earlier. A complete analysis of the ground roll should begin with the calculation of a dispersion curve for Rayleigh waves in a four-layered medium consisting of a thin low-speed surface layer, a 90-ft high-speed chalk layer, a low-speed layer 400 ft thick, and an infinitely thick high-speed sand layer. Since calculation for this very special case is extremely tedious to the point of being prohibitive, only an incomplete, qualitative discussion based on two-layer approximations will be given.

For a rough approximation we may replace the actual stratification by two separate two-layer problems as follows:

1) A high-speed layer (Austin chalk) over an infinitely thick low-speed layer (Eagle Ford shale).

2) A low-speed layer (Eagle Ford shale) over an infinitely thick high-speed layer (Woodbine sand).

C. Y. Fu (1946) has given a brief description of Rayleigh wave propagation in a two-layer medium where the surface layer has a higher speed than the substratum. For wavelengths small compared to the thickness of the surface layer, the phase velocity approaches the speed R_1 of Rayleigh waves in this layer. As the wavelength increases, the phase velocity decreases, approaching the speed

R_2 in the thick, low-speed intermediate layer. A Rayleigh wave of this type which was observed in the Delaware Basin has been described by Dobrin *et al.* (1954).

A qualitative sketch of the phase velocity curve (in dimensionless units) for the propagation of Rayleigh waves in a system consisting of a high-speed surface layer overlying a very thick low-speed section is shown in Figure 6. Here, β_1 and R_1 represent respectively the speed of shear waves and Rayleigh waves in the surface layer having thickness H; β_2 and R_2 are the corresponding speeds in the underlying low velocity medium; and L is the wavelength measured in the horizontal direction.

Only one point (indicated by a circle) has been computed and the curve has

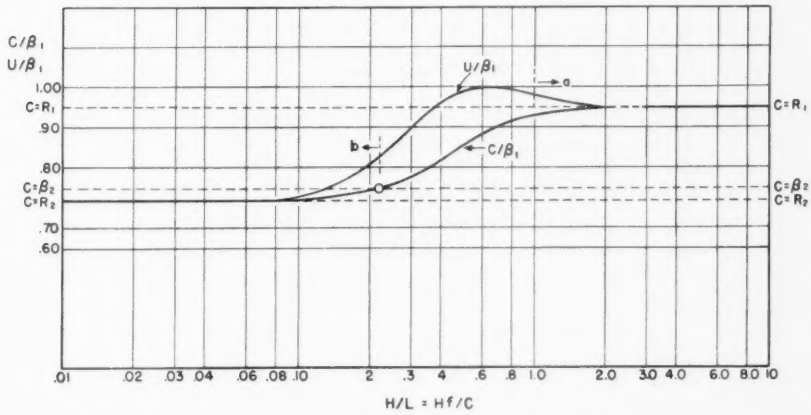

FIG. 6. Phase and group velocities vs. frequency for Rayleigh waves over high-speed surface layer. β_1 is shear speed of surface layer; β_2 is shear speed of substratum; H is layer thickness; L is wavelength; f is frequency; C is phase velocity; U is group velocity.

been sketched in on the basis of this point and the low-frequency and the high-frequency *asymptotic* values of phase velocity. To simplify calculation, incompressible media were assumed and the elastic constants assigned were $\beta_1/\beta_2 = 1.33$, $\rho_1/\rho_2 = 1.09$. The computation was based on a theoretical treatment by Love (1911, p. 16, eq. (62)). A group velocity curve U/β_1, computed from phase velocity, is also given.

In the region of short wavelengths (H/L large) the propagation is unattenuated except, of course, for selective absorption effects which are neglected in this discussion. As the wavelength increases, the waves begin to feel the influence of the low-speed medium, and slight attenuation occurs due to radiation of energy downward. Radiation loss increases with wavelength and becomes important when the wavelength begins to exceed the thickness of the surface layer. For $C<\beta_2$, where $L>H/.22$, radiation no longer occurs and wave propagation in this region is unattenuated. This is the physical basis for Fu's specification that Ray-

leigh waves cannot be transmitted without attenuation if their wavelength is shorter than that for which the phase velocity equals the shear speed in the lower medium. However, these low frequency waves, with wavelengths large compared to the high-speed chalk layer, are better approximated by the second case described above.

It is well known that in a dispersive medium waves associated with a given frequency are propagated with the group velocity for that frequency. The character of the R_1 arrivals at a given point can therefore be described qualitatively with the aid of the group velocity curve of Figure 6.

The earliest arriving surface waves travel with the maximum value of group velocity. These waves are in the region of large radiation loss and should be small at distances which are large compared to H. It is only at times corresponding to the intervals (a) $.95 < U/\beta_1 < .98$ (approx.), $H/L > 1.0$ (approx.) and (b) $.72 \leqq U/\beta_1 \leqq .83$, $H/L \leqq .22$ that waves with little or no attenuation arrive. These intervals are indicated by arrows in Figure 6. Waves corresponding to (a) would show little dispersion (hence, brief duration) since U/β_1 changes by only .03 as H/L goes from 1.0 to infinity. They would arrive as a Rayleigh wave consisting of a train of brief duration containing all frequencies larger than (very roughly) $f_a \cong 35$ cps ($Hf_a/C = 1.0$, $C = .93\beta_1$, $\beta_1 = 3{,}400$ ft/sec, $H = 90$ ft) except those filtered out by selective absorption and scattering.

The events marked R_1 on the seismograms of Figures 2 and 3, and the travel-time curve of Figure 4 agree with this simplified interpretation only in that they are Rayleigh waves of brief duration. Observation differs from the elementary theory in two respects:

1) Spectral components as low as 15 cps appear to be included in the R_1 pulse.

2) The observed phase velocity exceeds the group velocity of R_1 (the values are respectively 3,100 ft/sec and 2,700 ft/sec). The latter is difficult to reconcile with Figure 6 unless the thin surface zone of low velocity material indicated in the well log (Figure 1) is present along the profile. If this is the case, another dispersion curve would be applicable in which the phase velocity of R_1 would be lowered roughly 20 percent or less for wavelengths of the order of eight or more times the thickness of this zone. This number is estimated from a calculation by Lee (1934) for the effect of a clay layer on the phase velocity of Rayleigh waves in granite. The group velocity would be lowered by a somewhat greater amount than the phase velocity. Removing the effect of this zone on the velocity of R_1 could therefore increase the phase and group velocities to values which are more appropriate for the shear speed of 3,700 ft/sec obtained from the step-out for the directly transmitted shear waves.

The thin low-velocity surface zone cited above would be expected to prolong the duration of R_1 by the introduction of slower-traveling, higher-frequency waves. In an air shot a thin low-velocity surface zone would manifest itself in a train of constant-frequency waves following the air wave (see Press and Ewing, 1951). Both are observed in the seismograms of Figures 2 and 3, although

not as prolonged, consistent, and intense as might be expected. Poor transmission and irregularities in thickness of the low-speed zone would account for this.

The R_2 surface waves occur with frequencies in the range 5–10 cps and phase velocities of about 3,000 ft/sec. Since the corresponding wavelengths of 300–600 ft are of the order of the thickness of the Eagle Ford shale, the propagation may be represented approximately by the second case described above, that of a low-speed layer over an infinitely thick high-speed substratum. This case has been discussed frequently in the literature (see, for example, Dobrin *et al.*, 1951) so that only a brief description is necessary. A diagrammatic dispersion curve is

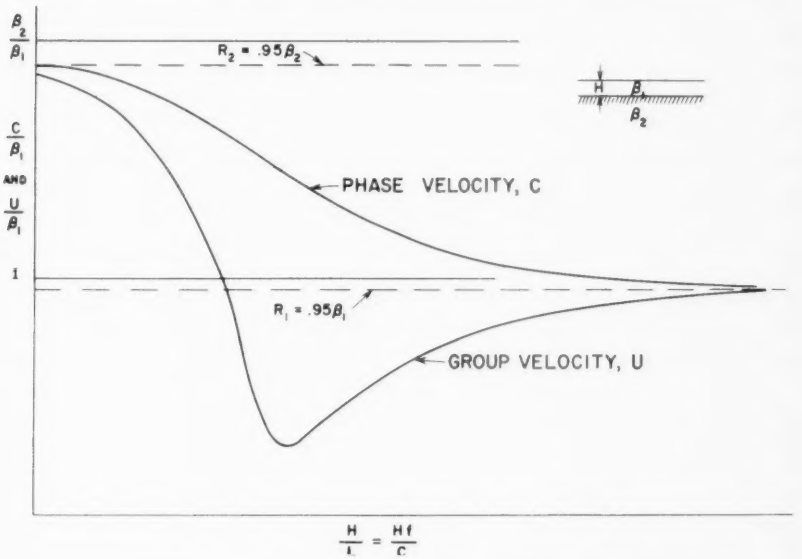

FIG. 7. Schematic dispersion curves for case of surface layer overlying higher-speed substratum. Symbols same as for Figure 6.

shown in Figure 7. Two branches of the group velocity curve occur, separated by a minimum value. In the branch to the left of the minimum, velocity increases with decreasing frequency. In the branch to the right, velocity increases with increasing frequency. For both branches, phase velocity exceeds group velocity. For a given phase (hence group) velocity, frequency is inversely proportional to layer thickness.

It is believed that propagation of the R_2 waves is controlled by a group-velocity curve of this type, particularly by that branch to the right of the minimum. The dispersion is not well developed because the propagation distance is too small and the contrast in shear velocity between the Eagle Ford shale and the Woodbine

sand is not very great. The low frequencies observed in the R_2 group occur because of the rather large thickness (400 ft) of the low-velocity layer.

Lower frequency waves corresponding to the left branch would fall below the recording range of the apparatus.

The more efficient excitation of R_2 by the deeper shot may be cited as further evidence for this interpretation.

It is obviously necessary to compute the dispersion curve and amplitude functions for the four-layered medium referred to earlier before a quantitative comparison between observation and theory can be made. The elementary approach is of limited use in explaining the character of the seismograms.

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GEOPHYSICS, VOL. XXI, NO. 2 (APRIL, 1956), PP. 299–304

THEORY OF A RESONANCE METHOD TO MEASURE THE ACOUSTIC PROPERTIES OF SEDIMENTS*

W. J. TOULIS†

ABSTRACT

The theory of resonance for a pressure release cylindrical chamber is explored and equations are derived for determining absolute values of the velocity of sound and the attenuation constant in sediment samples. The essential measurements that need to be made are the determination of the frequencies of the lower modes of resonance and the associated sharpness of resonance. Corrections are derived also for the finite thickness and the acoustic losses in the chamber walls.

INTRODUCTION

An acoustically resonating cylindrical chamber with soft or compliant walls can be used as a laboratory device to measure the velocity of sound and the attenuation constant in water saturated sediments. The velocity of sound may be determined directly from the resonant frequencies of the chamber while the attenuation constant is determined from the sharpness of resonance. To avoid confusion due to overlapping between modes, only the three lowest resonant modes have been used in experimental observations. For a cylinder 2 inches in diameter and 4 inches long these frequencies lie in the range from 23 to 32 kc per second. For measurements at lower frequencies a similar resonant chamber technique may be used. It involves a resonator of larger dimensions but a relatively small sample.

If resonators for sediments and liquids are to be used successfully, the walls of the chamber must be very thin or very compliant to minimize acoustic losses as a result of rigidity in the walls (Fay, 1952). Configurations of circular symmetry are relatively rigid compared with rectangular shapes and therefore do not have especially satisfactory pressure release surfaces. However, the most practical container shape for obtaining a relatively undisturbed sediment sample is cylindrical. A cylindrical plastic container with walls as thin as possible but rigid enough to maintain the cylindrical shape under the weight of the sediment sample is a satisfactory resonant chamber. If the resonance method is to be used for absolute measurements of velocity, corrections are necessary to account for the finite thickness of the cylindrical wall and the one closed end.

The accompanying paper by Shumway (1956) discusses the equipment, procedure and some measurements using the resonant chamber method.

THE RESONANT MODES OF A CYLINDRICAL CHAMBER

The resonant modes and the corresponding acoustic pressure distributions within an idealized pressure release wall resonator differ from the hard or high

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impedance type (Morse, 1948) in that the sound pressure at the wall must be zero. Thus the solution of the wave equation in cylindrical coordinates in an isotropic medium leads to an acoustic pressure distribution in a pressure release (or soft) wall resonator of the form

$$p = \begin{matrix}\cos \\ \sin\end{matrix}(m\phi)\ \sin\ (k_z z) J_m(k_r r) e^{-i\omega t} \tag{1}$$

where

$m = 0, 1, 2, \cdots$
ϕ is the cylindrical angular coordinate
z is the axial coordinate with $z = 0$ at one of the ends
r is the radial coordinate
$k_z = \omega_z/c$ is the wave number for the axial direction
$k_r = \omega_r/c$ is the wave number for the radial direction
c is the velocity of sound in the sample
t is time

and ω is the angular frequency. The solution of the wave equation also requires that

$$k^2 = k_z^2 + k_r^2 \tag{2}$$

where $k = \omega/c$. With the cylinder radius equal to a and the length equal to L, p must be zero at $r = a$ and at $z = L$. Then

$$\sin\ (k_z L) = J_m(k_r a) = 0$$

or

$$k_z L = l\pi \quad \text{where} \quad l = 1, 2, \cdots$$

and

$$k_r a = \pi\beta_{mn}. \tag{3}$$

The characteristic values of β_{mn} can be determined from a solution of the equation $J_m(\pi\beta) = 0$, with n being used to indicate the successive number of radial antinodes in each Bessel function of order m. Thus the resonant frequencies of the cylindrical chamber may be calculated from

$$f_{lmn} = \frac{c}{2}\sqrt{\left(\frac{l}{L}\right)^2 + \left(\frac{\beta_{mn}}{a}\right)^2} \tag{2a}$$

where $\beta_{mn} = \beta_{01} = 0.76555$ yields the lowest resonant frequency when $l = 1$ and corresponds to a pressure antinode at the center of the resonator. If the length of the cylinder is long compared to the diameter, the next higher modes will also have pressure antinodes along the axis and equal in number to l. If the

cylinder is short, the second lowest resonant mode will require $m=1$ and $\beta_{11}=1.2197$ with two pressure antinodes situated between the axis and the cylinder wall. Thus the dimensions of the cylinder should be chosen so that the various resonant modes do not overlap closely.

THE ATTENUATION CONSTANT

The attenuation constant of a viscous liquid may be determined by measuring the Q or sharpness of resonance of a resonant chamber filled with the liquid. Experimentally, this is accomplished by measuring the width of the resonance curve at the half-power points, or

$$Q = \frac{f_{lmn}}{\delta f} \tag{4}$$

where f_{lmn} is the resonant frequency of the lmn mode and $\delta f = f_2 - f_1$ if f_2 and f_1 are, respectively, the frequencies above and below the resonant frequency at which the pressure amplitude drops by 3.01 db. For liquids that are not extremely viscous $f_2 - f_{lmn}$ should equal $f_{lmn} - f_1$.

The relationship between Q and the attenuation constant may be established through the definition of Q for a resonant chamber

$$Q = \omega \frac{\text{energy stored}}{\text{energy lost/second}}. \tag{5}$$

The energy density at any instant at a given point within the resonator is the sum of the kinetic and potential energies averaged over a small volume about the given point or

$$D = p^2/2\rho c^2 + \rho u^2/2 \tag{6}$$

where p is the instantaneous pressure, ρ is the density, and u is the instantaneous particle velocity averaged over the unit volume. Over the period of a cycle the energy within the chamber oscillates from positions of high potential energy to positions of high kinetic energy with a velocity c which is characteristic of the medium. If sound absorption is assumed to occur in the medium (typical to the problem under consideration) and the walls are assumed to be ideal, then the energy stored in the chamber will decrease by a factor of 2α for each unit of length the energy flows. Assuming a steady state condition, whereby the acoustic losses are replenished by an external source, the fractional energy that must be supplied by the source over a period of unit time is $2\alpha c$. As a result, equation (5) may be rewritten as

$$Q = \omega \frac{W}{2\alpha c W} = \frac{\omega}{2\alpha c} \tag{5a}$$

where W is the integral of D over the volume of the chamber. It should be noted

at this point that in cases where frictional losses originate at the wall (Lambert, 1953), the velocity of energy flow, or the group velocity, is no longer the same as the characteristic velocity c of the medium, but depends on the geometrical configuration of the chamber.

Equation (5a) may be rewritten with the aid of equation (2) in the form

$$\alpha = \frac{\sqrt{k_z^2 + k_r^2}}{2Q} = \left(\frac{\pi}{2Q}\right)\sqrt{\left(\frac{l}{L}\right)^2 + \left(\frac{\beta_{mn}}{a}\right)^2} \tag{5b}$$

which is the expression for the attenuation constant in nepers per unit length due to the medium in a cylindrical resonator, assuming negligible losses at the walls.

CORRECTIONS DUE TO WALLS

The resonant frequencies and the coefficient of attenuation for the cylindrical chamber have been derived on the assumption that the walls are negligibly thin or have the same properties as the enclosed medium. In practice neither of these assumptions can be entirely justified. Hence equations (2a) and (5b) must be modified to account for the wall effects.

The nature of the correction for the velocity of sound can be resolved by rewriting equation (6) as

$$D = p^2/2M + \rho u^2/2 \tag{6a}$$

where $M = \rho c^2$ is the bulk modulus on the assumption that the chamber and its contents behave like a fluid and, therefore cannot support shear waves. Equation (6a) suggests that in positions within the chamber where the sound pressure is high and u approaches zero the energy density is inversely proportional to M; conversely, in positions where the pressure approaches zero, as at the walls, the energy density depends directly on the density. Since the relative density is the significant factor at the walls, then L and a in equation (2a) should be defined as

$$L = L_0 + t\left(\frac{\rho_w}{\rho_s} - 1\right)$$
$$a = a_0 + t\left(\frac{\rho_w}{\rho_s} - 1\right) \tag{7}$$

where L_0 and a_0 are the geometrical values measured to the outside of the container, t is the wall thickness in each case, ρ_w is the density of the wall material, and ρ_s is the density of the sediment within the chamber.

The correction for the attenuation constant as a result of acoustic losses in the walls should be determined experimentally by using bubble-free water in place of a sediment sample. The approximate form of the correction is

$$\alpha_w = \omega/2Q_w c \tag{5c}$$

where Q_w is the Q with water in the chamber. It should be noted again that the group velocity does not properly enter into equation (5c) if the latter is to be consistent with equation (5b). Essentially the same argument suggests that c should be the velocity of sound in the sample rather than in the water. Thus equation (5b) will be sufficiently accurate if Q is redefined as

$$\begin{aligned} 1/Q &= 1/Q_s - 1/Q_w \\ &= \frac{\delta f_s - \delta f_w}{f_{lmn}} \end{aligned} \tag{8}$$

where the subscript s refers to measurements with sediment in the resonator and w with water in it.

CONCLUDING REMARKS

Absolute measurements of the velocity of sound and the attenuation constant of sediments may be determined by the resonant chamber method provided the essential corrections are taken into consideration. Equation (2a) yields the velocity of sound if the effective length and radius of the cylindrical resonator are defined as in equation (7). However, measurements by Shumway (op. cit.) with distilled water as the sample indicate that the velocity of sound determined by the three simplest resonances differ by small amounts from the accepted value for water. This suggests that the rigidity of the resonator walls was not completely eliminated. Thus if acoustic energy trapped in the walls is the source of error, then the second mode should be the most reliable inasmuch as the phase differs by 180° between the upper and lower portions of the cylinder. From this point of view, the first mode would be the least reliable of the three. Since the sharpness of resonance with sediments is broader than with water by a factor of about 10, the small deviations in velocity between the modes may be neglected.

The attenuation constant in a sediment may be determined through equation (5b) if Q is defined as in equation (8). Past experience with measurements using compliant wall resonators suggests that gaseous bubbles could have an important bearing on the experimental observations with sediments. The large spread in attenuation values observed by Shumway may be due in part to the presence in samples of naturally occurring bubbles and possibly, in part, to variations in shear viscosity with particle size and the degree of packing.

ACKNOWLEDGMENTS

The author is indebted to George Shumway for many interesting discussions and suggestions.

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GEOPHYSICS, VOL. XXI, NO. 2 (APRIL, 1956), PP. 305-319, 6 FIGS.

A RESONANT CHAMBER METHOD FOR SOUND VELOCITY AND ATTENUATION MEASUREMENTS IN SEDIMENTS*

GEORGE SHUMWAY†

ABSTRACT

Sound velocity and attenuation measurements in unconsolidated marine sediments have been made by a resonance method which utilizes a thin-walled plastic cylinder as a pressure-release container to hold samples. Velocities were determined from resonant frequencies which lay between 23 and 36 kc/sec for the 2 inch diameter by 4 inch long cylindrical container used. Attenuation was determined from the sharpness of the resonant modes. Relatively undisturbed sediment samples were obtained by diver, in shallow water, using the same plastic containers in which the acoustic measurements are made. Deep sea samples were obtained by cutting sections from cores which were taken in plastic tubes.

Velocities for shallow water sediments in the San Diego area ranged from 4,840 ft/sec (0.978 times sea water velocity) for fine silt to 5,680 ft/sec (1.147 times sea water velocity) for medium sand, measured at 60°F. and atmospheric pressure. Velocities in deep-sea red clay samples ranged between 0.980 and 1.040 times the sea water velocity, at 60°F. and atmospheric pressure. Attenuation coefficients for shallow-water San Diego sediments varied from about 1 to 4 db/ft for silts, to about 3 to 8 db/ft for sand.

INTRODUCTION

A method for measuring compressional sound velocity, and attenuation, in water-saturated sediments is suggested by Toulis (1956) by determining the resonant frequency and sharpness of resonance of sediment samples in a pressure-release or soft-walled chamber. The present paper describes and discusses the equipment necessary for these studies, the procedures involved, and the degree of accuracy which is obtained, and presents the results of some preliminary studies with sediments.

Toulis (1956) shows that compressional sound velocity, c, and attenuation in nepers per unit length, α, for a cylindrical chamber with infinitely thin walls filled with a non-rigid material are related to resonant frequency, f_{lmn}, and to sharpness of resonance, Q, by the equations

$$f_{lmn} = c/2\left[(l/L)^2 + (\beta_{mn}/a)^2\right]^{1/2} \tag{1}$$

and

$$\alpha = \pi/2Q\left[(l/L)^2 + (\beta_{mn}/a)^2\right]^{1/2} \tag{2}$$

where L = cylinder length, β_{mn} = a constant, a = cylinder radius, and l = number of pressure antinodes in the axial direction. The subscript n indicates the number of pressure antinodes along a radius, and m = one half of the number of angular antinodes. For the resonances used in this study, $m = 0$, $n = 1$, $l = 1$, 2, or 3, and $\beta_{mn} = 0.76555$.

The resonance method is well suited as a laboratory method of studying sedi-

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ment acoustics. Resonance measurements were made in the frequency range 23 to 36 kc, which is the frequency range of much underwater sound work. At these frequencies the particle size of even a coarse sand is small compared with wave length, which is not the case for the megacycle frequency range used for laboratory studies by pulsing methods. A favorable feature of the resonance method is the ability to measure attenuation and velocity almost at the same time.

Laboratory studies of the acoustic properties of artificial sediments have been made by Mifsud (1953) and others using pulse techniques. A resonance technique was used by Iida (1938, 1939) to study both natural and artificial sediments. An attempt to use a rigid-walled resonant chamber for acoustic studies of sediments was not particularly successful (U.C.D.W.R., 1945).

A difficulty in making laboratory studies of sea floor sediments is that of providing samples for measurement which are relatively undisturbed and which are representative of the bottom. For shallow water sediments this problem has been overcome in the present work through the use of self-contained underwater breathing apparatus. The container in which the sample is held for the resonance measurements is carried underwater by diver, where a relatively undisturbed sample is collected. Then it is transported to the laboratory while immersed in water, so there is no chance for water to be lost nor for air bubbles to be introduced.

Most of the sediment samples used in this study were obtained as part of a general program to study acoustic properties of shallow water sediments which is described by Hamilton, Shumway, Menard, and Shipek (1956). The sediment studies made with this resonant chamber method constituted part of the program, and are presented more fully in the above report.

EQUIPMENT

Electronic equipment

The major items of electronic equipment needed for these studies consist of a heterodyne signal generator with a fine frequency control, an amplifier, and a vacuum tube voltmeter. Two crystal phonograph pick-ups were used as trans-

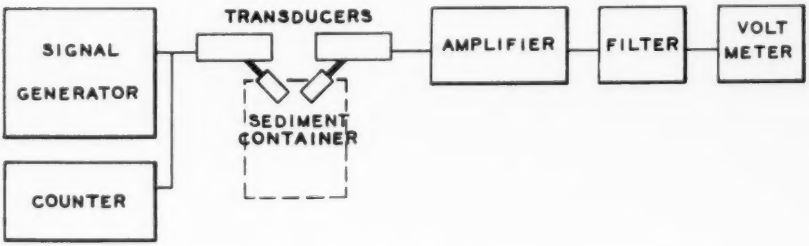

FIG. 1. Schematic diagram of equipment for resonance measurements.

ducers, one to excite the sample to resonance and the other to detect the resonance. A variable frequency filter was used to minimize extraneous signals. An electronic counter was used to monitor the oscillator frequency. The arrangement of the apparatus is shown in Figures 1 and 2.

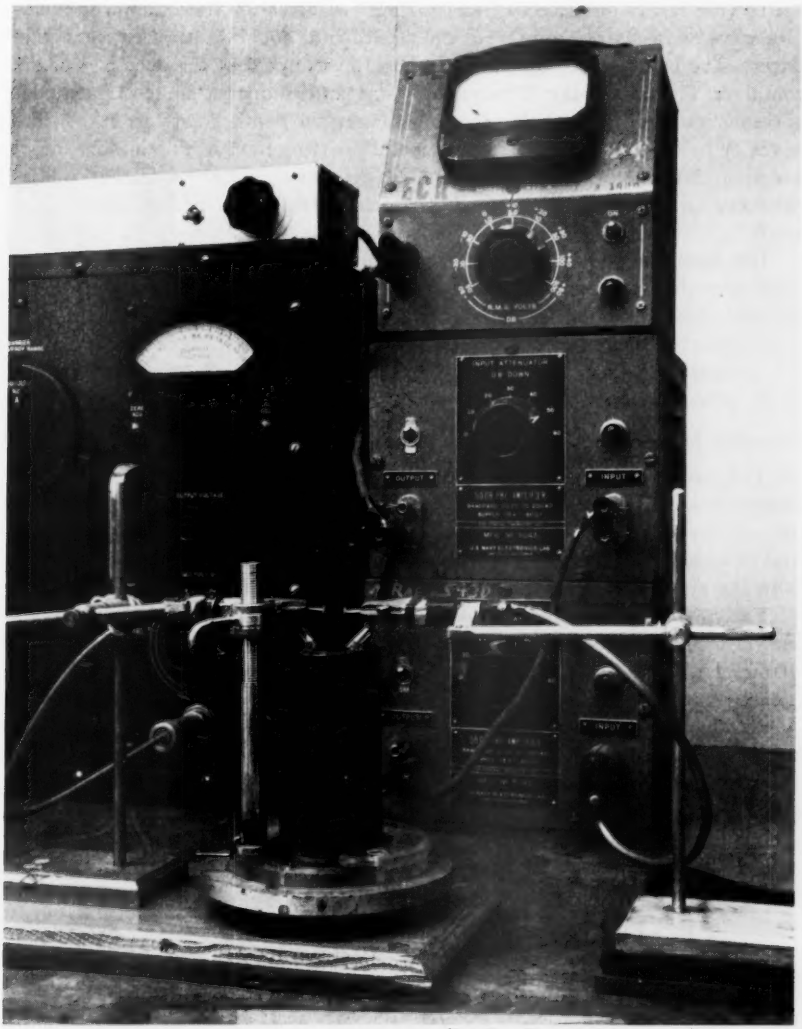

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FIG. 2. Equipment used for resonance measurements.

Transducer location

In order to transfer acoustic energy between the transducers and the sediment, a 1/16 inch diameter brass rod with a piece of $\frac{1}{4}$ inch diameter plastic rod fastened to one end, was attached to each transducer in place of a phonograph needle (Fig. 2). In addition to transmitting mechanical motion, the plastic paddles serve as insulators to prevent direct electrical coupling between the transducers. The paddles are dipped partly into the sediment at the open end of the container. The positioning of the paddles is not critical for the simple axial modes of resonance used. It is merely necessary to keep the paddles away from the sides of the cylinder and to keep the separation of the two sufficient to minimize direct coupling. Within these general limits, changes in the location of the paddles produced no detectable change in resonant frequency or in the type of resonant mode.

In a resonating liquid sample (and also in clay slurries) the type of resonant mode was detected by noting the damping effects produced by a very small piece of absorbing material, such as rubber or cork, on the end of a thin wire. When the absorbing material was placed within a region of alternating high and low pressure the resonance intensity was markedly reduced, hence the pattern of the pressure-change areas may be mapped.

Container for sediments

The material for the sediment containers must have acoustic properties somewhat similar to water and water-sediment mixtures and yet it must be rigid enough to allow the container to be forced into the bottom to take the sample and to withstand distortion due to the weight of the contained sediment when it is in the air. Certain plastics meet these requirements fairly well.

Early containers were made from the same transparent cellulose acetate butyrate tubing as is used for liner in sea floor coring apparatus. The outside diameter was 2 inches, the length 8 cm, and the average wall thickness 0.069 inches. A 1/16 inch thick plastic (Plexiglas) disc was cemented on one end. A 3/32 inch diameter hole was drilled in this end piece near the edge of the tubing, and a piece of plastic sealing compound was stuck around the hole so that the hole could be plugged easily after the container was forced into the sediment.

Sediment samples were taken by a diver who forced the container into the sediment, bottom end up, then dug away at one side of the container and placed a cover under the open end (Fig. 3). The small hole in the closed end of the container, which allowed water to escape as the container was pushed into the sediment, was plugged prior to fastening on the cover.

A container of this first type (designated Type I) filled with distilled water at 70°F. yielded the following:

Vibration	*Resonant Frequency*	*Q*
Mode (101)*	24.087 kc	454
Mode (201)*	28.693 kc	294
Mode (301)*	35.157 kc	200

* These indices are, respectively, the l, m, and n of Equations (1) and (2).

Because distilled water alone has an attenuation constant too low to be detected by this apparatus, the low Q values must be attributed to losses in the container walls.

An improved container (designated Type II) was made from transparent cellulose acetate butyrate tubing with an outside diameter of 2 1/16 inches, a length of 10 cm, and a wall thickness averaging 0.044 inches. Transparent rigid

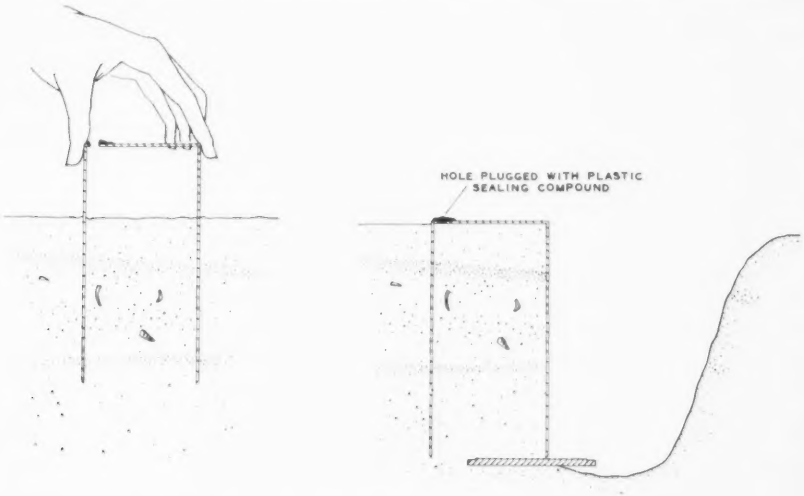

FIG. 3. Method of obtaining shallow water sediment samples by diver.

vinyl plastic 0.020 inches thick was used for the bottom. These somewhat larger containers filled with distilled water at 70°F. gave the following:

Vibration	*Resonant Frequency*	*Q*
Mode (101)	21.890 kc	909
Mode (201)	26.138 kc	909
Mode (301)	30.916 kc	322

The lower frequencies and higher Q's show this container to be superior to Type I.

TEMPERATURE CONTROL

The temperature at which the resonance measurements are made must be known with reasonable accuracy because of the pronounced effect of temperature on sound velocity in water, and presumably also on water filled sediments. After the acoustic measurements were made on the sediment, a partial immersion thermometer was pushed into the sediment for a terminal temperature. The temperature change occurring during the course of a measurement was assumed to be nearly the same as that for a container filled only with water, which was placed near the sediment container during the measurements and which

initially had the same temperature as the sediment. For each resonance mode measurement the temperature probably can be determined to $\pm 0.2°$F., corresponding to a velocity difference in water of ± 1 ft/sec.

VELOCITY DETERMINATION

Calculation

For a cylinder of a given size and a particular resonant mode, Eq. (1) shows that velocity is directly proportional to resonant frequency. Toulis (1956) however shows that it is necessary to introduce a correction for the finite thickness of the container walls by defining L and a in Eq. (1) and (2) as

$$L = L_0 + t(\rho_w/\rho_s - 1) \tag{3}$$

and

$$a = a_0 + t(\rho_w/\rho_s - 1) \tag{4}$$

where L_0 and a_0 are dimensions measured to the outside of the container, t is the thickness of the cylinder end wall in Eq. (3) and of the cylinder side wall in Eq. (4), ρ_w is the density of the container end wall material or side wall material in the respective equations, and ρ_s is the density of the sediment or water in the container.

Velocity values may be calculated either directly from Eq. (1), or by comparison of sediment resonances with distilled water resonances. Both methods require that the physical dimensions of the container be known accurately so that the wall corrections can be made. The comparison method has the advantage that restraints on the resonant system due to the unavoidable stiffness of the container walls tend to cancel out.

Velocity values reported in this paper were calculated by the comparison method using Eq. (5) which follows. Consider a container set to resonance first with distilled water in it, then with sediment in it. Referring to Eq. (3) and (4), let the effective container dimensions L and a be represented by L_1 and a_1 when distilled water is in the container, and by L_2 and a_2 when sediment is in the container. Let c_{water}, c_{sediment}, f_{water}, and f_{sediment} be the sound velocities and resonant frequencies with water and sediment, respectively, in the container. Then by algebraic manipulation of Eq. (1) an expression for sediment velocity is obtained which employs the wall corrections:

$$c_{\text{sediment}} = \frac{f_{\text{sediment}}}{f_{\text{water}}}\, c_{\text{water}}\, \frac{L_2 a_2}{L_1 a_1} \sqrt{\frac{a_1^2 l^2 + L_1^2 \beta_{mn}^2}{a_2^2 l^2 + L_2^2 \beta_{mn}^2}}. \tag{5}$$

Distilled water studies

To determine the best possible reproducibility of resonant frequency for the two types of containers and to help evaluate the relative usefulness of the three

resonant modes, studies were made with distilled water. With a container of each type 30 determinations of the resonant frequency were made for each mode. For each determination the amount of water in the container was within 0.1 milligram of the amount used the first time. These resonance measurements were made between 72°F. and 82°F.

Using equation (1), the distilled water velocities were calculated, allowing for side and end wall corrections. Plots of velocity versus temperature for the three modes with the Type II container (Fig. 4) give an idea of the reproducibility which can be expected under favorable conditions. For comparison, literature values of velocity made by interferometer (Siefen, 1938; Willard, 1947; Del Grosso, 1952) are given. The mode (201) velocity values deviate by less than 2 ft/sec from a smooth curve which might be drawn through them. Deviations for mode (301) are slightly greater, amounting to a few feet per second at the most. In general the mode (301) values are lower than those for mode (201) by 2 to 3 ft/sec, but the values for both modes agree rather well with the interferometer measurements. The scatter for mode (101) is greater than for the other two modes, and the values lie between 25 and 30 ft/sec greater than the literature values and the values for the other two modes.

With the Type I container (thicker walls) the scatter of points for each mode (data not illustrated) is greater than for the Type II container. Again, mode (201) gives the best results, and the values of velocity would deviate from a smooth curve which could be drawn through them by as much as 8 ft/sec. For mode (301) and mode (101), deviations of as much as 15 ft/sec occur. All of the velocity values for all of the modes are greater than the literature values at corresponding temperatures. Mode (201) values are generally about 20 ft/sec higher, mode (301) values about 17 ft/sec higher, and mode (101) values about 50 ft/sec higher.

Toulis (1956) suggests that mode (101) would be the least reliable of the three, and that mode (201) would be the most reliable. These distilled water studies agree with his discussion and help substantiate it. Further agreement is found in the sediment studies, whereby mode (201) was detected in almost every sample, mode (301) in most samples, but mode (101) was detected in only about one third of the samples.

Accuracy of velocity determinations

An evaluation of the more important possible sources of random error in the resonant frequency measurements gives a rough measure of the accuracy that might be expected under the most favorable conditions. The following errors can be considered as the one standard deviation limits. Relatively high-loss sediments, i.e., sands, give broad resonance peaks, however the frequency of the top may be estimated to within 100 cycles/sec, which at 30 kc/sec is an error of ± 0.33 percent. Temperature measurement errors affect frequency by ± 0.03 percent. The length of the cylinder of sediment can be determined to about ± 0.5 mm, which would affect frequency by ± 0.20 percent. The total experimental

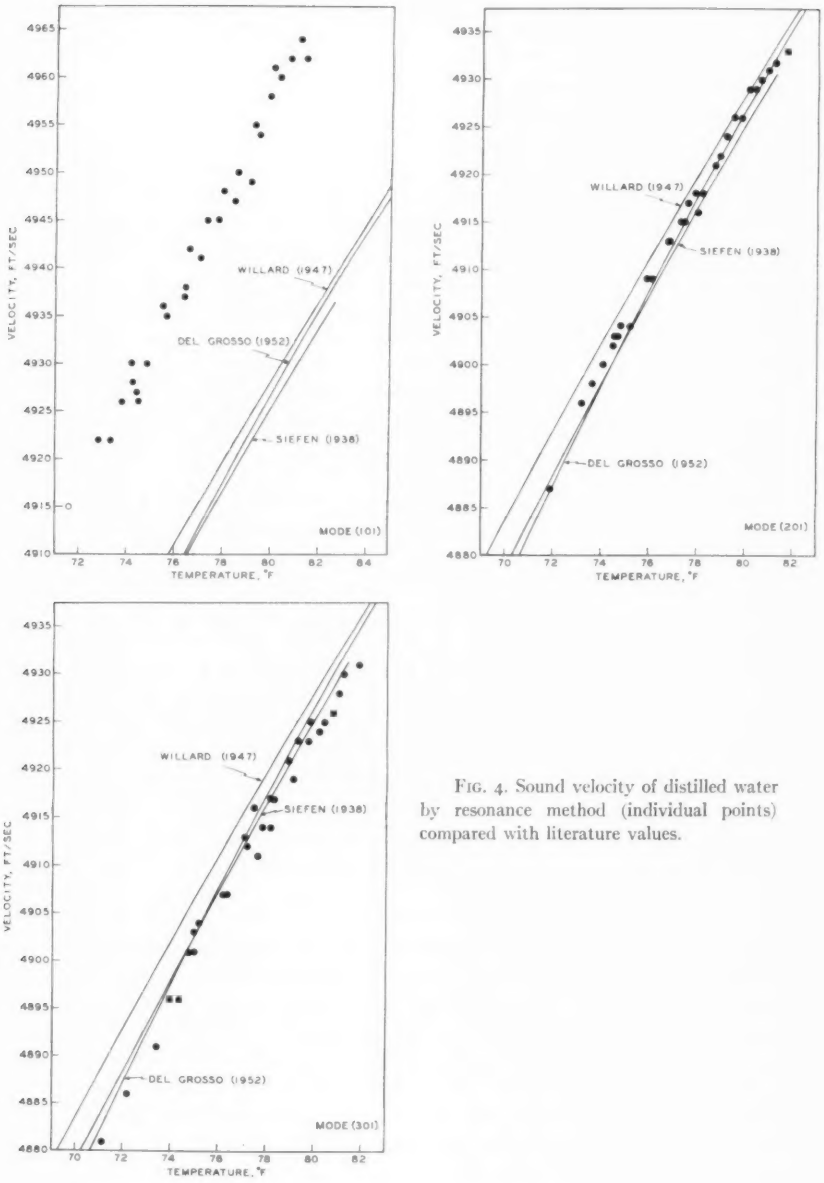

FIG. 4. Sound velocity of distilled water by resonance method (individual points) compared with literature values.

error is ±19–23 ft/sec for velocities between 5,000 and 6,000 ft/sec. For fine grained sediments (silt and clay) the resonant frequency usually can be measured to within ±10 cycles/sec, which would reduce the error to ±10–12 ft/sec.

The errors involved in the field measurements which have been made are larger than this lower limit, of course, and the topic is considered further in the section *Shallow water sediments*.

ATTENUATION DETERMINATION

The attenuation constant in sediment samples was determined using equation (2). For each of the three modes used, the width of the resonance peak between the half-power points was measured in terms of frequency. Allowance is made for losses due to the plastic container alone, determined from measurements made with distilled water.

During the sampling and transportation of the sediment, features may arise in it which change its attenuation. The most important of these is the possible production of *unnatural* gas bubbles within the sediment as a result of temperature change, disturbance, or change in pressure. Bubbles may form when water, saturated with air, is raised in temperature. An attempt was made to keep the temperature rise of the sediment as small as possible after sampling, and usually it was less than 10°F. Most of the sediment samples, however, apparently are undersaturated with oxygen, for they contain decaying organic matter and smell of H_2S, so the formation of oxygen bubbles due to oversaturation probably is negligible. The breakdown of organic matter may release some gases during the course of the measurements, but this is important only if the amount is different than that which would have developed in the same time if the sediment had been left in place on the sea floor. If gas bubbles are in the sample when it is taken from the sea floor, then they represent a natural condition of the sediment and would affect its attenuation constant.

SEDIMENT MEASUREMENTS

Shallow water sediments

During the period in which techniques for the resonant chamber method were being developed and the equipment improved, a broad program for studying the mass physical and acoustic properties of shallow water sediments was under way at the Navy Electronics Laboratory, as described by Hamilton, Shumway, Menard, and Shipek (1956). Thirty-four stations were made in the San Diego region. Acoustic studies by the resonant chamber method were part of this program. A variety of sediment sizes was encountered, and velocities and attenuations were measured on natural sediments ranging from fine silt to coarse sand. The acoustic properties measured for each resonant chamber sample together with other physical and geological properties for the samples are given by Hamilton, et al.; the velocity values reported, however, did not have the wall correction applied to them. The effect of the wall correction is to lower the reported values between 50 and 150 ft/sec.

Corrected velocity values for the sediments of the San Diego area are presented here (Fig. 5). The velocities, corrected to 60°F., ranged from 4,840 ft/sec to 5,680 ft/sec. The lowest values were found for the sediments of smallest median grain diameter, and a general trend of decreasing velocity with decreasing median grain diameter can be noted. Velocities lower than that of sea water were measured for most of the silty sediments.

The points in Fig. 5 represent averages of the values for as many of the three modes as were detected for each sample. For more than half of the samples the

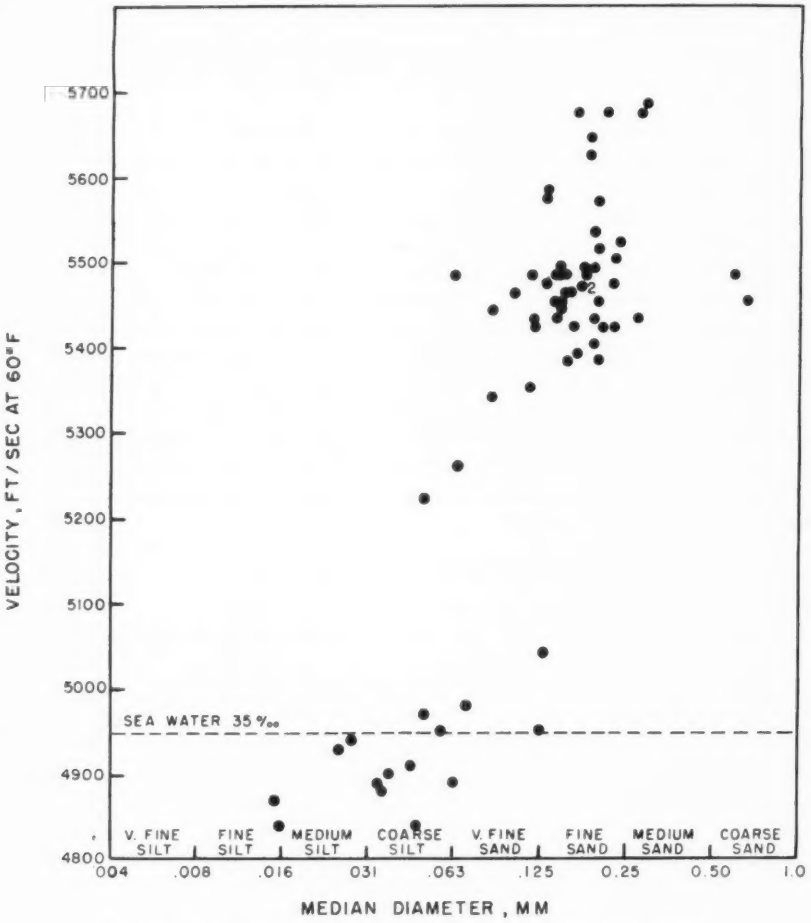

FIG. 5. Sound velocity vs median grain diameter for shallow water sediments.

first mode could not be detected. In a few instances two of the three modes gave values in good agreement, but the remaining mode was sufficiently different to appear in error, so it was discarded. The second resonant mode was the easiest of the three to detect with sediments, although the third mode usually was found also. Mechanical analyses of the sediments showed that many of the samples contained scattered pieces of shell, and some had pebbles in them. Only when these particles reached a size of more than about 2 cm in at least one dimension did difficulties sometimes arise in determining resonances.

An estimate of the experimental errors inherent in the velocity measurements already has been considered. The actual measurements presented here were made under varying conditions and with techniques which gradually were improved during the course of the experiments. A comparison of the results by resonance with velocity measurements made *in situ* at the same stations by the pulse method has been given by Hamilton, et al. (1956). The fact that the velocity values by resonance are corrected slightly in the present paper (Fig. 5) does not substantially change the favorable agreement of results by the two methods.

For 17 stations, where sediments ranged from medium sand to sand-silt-clay a correlation coefficient of +0.89 exists between results by the two methods. The mean difference between velocities by the two methods is 2 ft/sec, and the standard deviation of this difference is 106 ft/sec. The standard deviation of the experimental error in the velocity measurements for the 17 stations was found to be about 100 ft/sec. This error value was determined by assuming that at each station the sediment was uniform enough that both experimental methods measured sediment with the same true velocity, and that disagreements between results by the two methods were due to experimental errors. This assumption, however, is only true to a limited extent, for in the shallow water locations where the sampling was done and the *in situ* measurements were made the sediments do vary in composition over distances measurable in feet. At each station two or three resonant chamber samples were taken, with separations of a few feet between them; *in situ* probe determinations made at the same stations were located no closer than within a 6-ft diameter circle, and the resonance samples and the probe determinations were separated by a few feet or yards from each other. Hence, if the comparison between the two methods could be made under ideal conditions, better agreement should be expected, and the experimental error as determined above for the resonance measurements should be smaller.

Attenuation coefficients for the shallow water sediments studied range from about 1 to about 8 db/ft. For any given sample the agreement between attenuation values for the three modes of resonance usually is not good, even when allowance is made for a frequency squared dependence in the attenuation. Differences of a few db/ft between modes are frequent. However, the mean of all mode (101) values is only 0.1 db/ft lower than the mean of all corresponding mode (201) values when a frequency correction is made; the mean of all mode (301) values is about 1 db/ft lower than the mean for all corresponding mode

(201) values. Thus agreement is reasonably good when a number of samples is considered. It is possible that sample inhomogeneity affecting one mode differently than another may contribute to differences with individual samples.

Attenuation values for mode (201) show that losses in the silty sediments are less than in sands (Fig. 6), however relatively few values for silty sediments are available. Values for mode (101) and mode (301) are fewer in number and do not indicate a trend as clearly as does mode (201), hence they are not presented here.

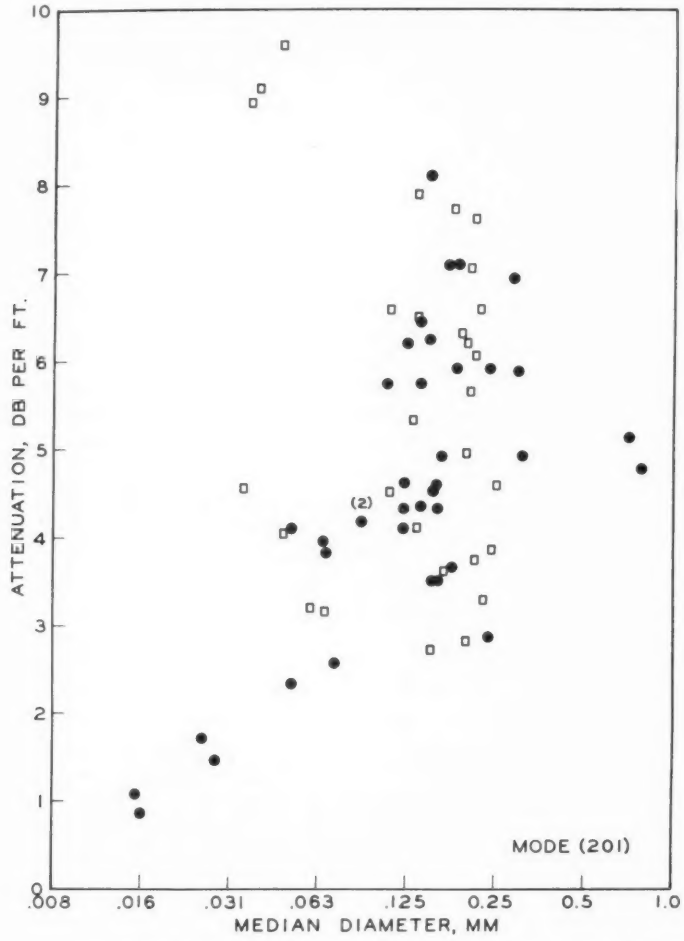

FIG. 6. Attenuation coefficient vs median grain diameter for shallow water sediments, mode (201). Solid circles are values obtained using container Type II and have more significance than open square values from Type I containers.

Deep sea sediments

Deep sea sediments may be studied by this resonance method also, provided suitable samples can be obtained. Deep sea cores frequently are obtained in the same 2-inch diameter tubing as used for the Type I container. By cutting a section out of such a core and placing a plastic disc on the bottom end, a sample is provided. For the samples to be useful, however, it is imperative that neat transverse cuts of the plastic tubing plus the sediment be made and that the bottom disc be placed on the end of the sample without trapping air bubbles. A technique was developed whereby the cutting and placing of the end disc was done entirely under water. A bucket with a hole in the bottom large enough to take the tubing was used and the desired portion of the core was placed within the bucket. The

TABLE I

SOUND VELOCITIES IN DEEP SEA CORES AT 60°F., ONE ATMOSPHERE PRESSURE

Sample position in core, cm from top	Latitude Longitude	Water depth, fathoms	Velocity, ft/sec	Velocity, km/sec.	Wet density gm/cc	Percent water by weight, corrected for salt	Sediment median diameter, mm
68–76	27°32′ N 154°06′ W	3,120	5,150±60	1.570±.020	1.46	52.3	0.002
29–37	21°32.8′ N 157°08.8′ W	2,254	5,150±60	1.570±.020	1.48*	48.1*	0.007
8–16	23°21.5′ N 156°28.7′ W	2,326	4,980±60	1.520±.020	1.48†	50.3†	0.003
2–10	31°51.9′ N 121°30.8′ W	2,310	4,850±60	1.480±.020	1.30	62.1	0.002

* These data taken at a position 43 cm from top of core.
† These data taken at a position 91 cm from top of core.

bucket was filled with water and the tubing cut underwater with a specially made cutter.

Sound velocities in a few deep sea cores were measured in the course of developing the above technique (Table I). As with the shallow water sediments, velocities were corrected to 60°F. for comparative purposes, assuming that the sediment velocity change with temperature is similar to that of sea water for small temperature changes. Velocity values were in the range 4,850 to 5,150 ft/sec (1.480 to 1.570 km/sec) at atmospheric pressure. Bottom water in the eastern North Pacific, where the samples were taken, has a salinity of about 34.6 °/₀₀ (Sverdrup, et al., 1942). Its velocity would be 4,948 ft/sec at 60°F. and atmospheric pressure (Del Grosso, 1952). One of the sediment values was lower than this water value.

The hydrostatic pressure effect on velocity in sea water at the depths of the samples is to increase the velocity by about 250 to 300 ft/sec (this follows from

Kuwahara, 1939, and others). Laughton (1955) showed experimentally that the hydrostatic pressure effect on the velocity of an uncompacted deep sea clay sample is similar to that on sea water alone.

CONCLUDING REMARKS

The phenomenon of the sea floor sediments having sound velocities lower than the sea water overlying them has been brought to light recently from more or less simultaneous studies conducted in various parts of the world. Pettersson (1954) mentioned that Weibull has determined sediment velocities from deep sea seismic work which are lower than sea water. Officer (1955), also working with deep sea seismic data, reached a similar conclusion. Officer found, however, that a velocity dispersion in the sediment probably limits the lower-than-water velocities to frequencies below a few thousand cps in an uppermost seismic layer. In the present paper, low velocities determined by the resonance method at frequencies between 23 and 35 kc are reported for surface sediments from both the deep sea and shallow water. Lower-than-water velocities also were determined in shallow water sediments by the *in situ* pulse method at 100 kc/sec (Hamilton, Shumway, Menard, Shipek, 1956); the low velocity phenomenon is discussed by Hamilton (1956).

Officer's interpretation that, on a seismic scale, lower-than-water velocities are not found at frequencies exceeding a few kc/sec does not necessarily conflict with the low-velocity measurements made at higher frequencies by the resonance method. On a deep sea seismic scale a sediment layer is hundreds of feet thick. If in the upper few feet or even few tens of feet of such a layer there was a velocity increase downward, then it might be reasonable to have a lower-than-water velocity for 20 kc to 100 kc sound near the surface of the sediment, yet on a seismic scale to have the characteristics Officer reports.

In the simple resonance theory presented by Toulis (1956) the effect of the mass of the container walls was considered, but the effect of the elastic restraints was assumed to be relatively small. Evidence for the restraints was seen in the different Q values for the two types of containers used, which had walls of different thickness. The effect of such restraints was minimized, however, by using walls as thin as possible and by determining velocities by comparison with distilled water. A second point of concern is that of rigidity in the sediment samples. In Toulis' treatment it was assumed that the sample rigidity is negligible. Possibly most marine sediments predominating in silt and clay fractions have rigidities so low that the assumption is justified. The somewhat more rigid structure of sands, however, may introduce complications to the resonant system.

The resonance method, using a soft-walled container, has been shown to be a useful laboratory method for measuring both sound velocity and attenuation in unconsolidated sediment samples. The studies presented, here, corroborated by data obtained using the *in situ* probe method (Hamilton, Shumway, Menard, and Shipek, 1956) establish the general range of sound velocities in surface sea

floor sediments. Furthermore, the general range of attenuation coefficient values for these sediments is obtained.

ACKNOWLEDGMENTS

I am particularly grateful to Dr. W. J. Toulis for his advice and encouragement during this work. Drs. E. L. Hamilton and H. W. Menard discussed the work with me on numerous occasions, and as divers helped me in the collection of field samples. Drs. Carl Eckart, L. N. Liebermann, R. W. Raitt, and Philip Rudnick of the University of California have given helpful suggestions in the preparation of this paper.

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GEOPHYSICS, VOL. XXI, NO. 2 (APRIL, 1956), PP. 320-336, 11 FIGS.

A MARINE SEISMIC MODEL*

GEORGE P. SARRAFIAN†

ABSTRACT

A model for the study of marine seismic phenomena is described. Study of multiple-reflection phenomena forms the basis for the course of experiments. It is shown that the multiple-reflection phenomenon of a disturbance with slowly decaying amplitude may be duplicated in the model. Multiple-reflection problems are studied in which the bottom of the water layer is tilted or thin. A mass of air bubbles is shown to be of use in attenuating multiple reflections. The possible application of the marine model in a search for information about certain problems in field prospecting is suggested.

INTRODUCTION

In recent years several investigators have attacked problems concerning seismic wave propagation by means of small-scale models whose dimensions and acoustical properties are readily controllable (Evans et al., 1954; Howes et al., 1953; Kaufman and Roever, 1951; Levin and Hibbard, 1955; Oliver et al., 1954; Press et al., 1954). This paper describes an application of this general method to the study of certain problems encountered in marine seismic prospecting.

One of the most important problems encountered in seismic prospecting in water-covered areas concerns the case in which the water layer is shallow and overlies a comparatively rigid bottom. Under these conditions, a large proportion of the useful seismic energy liberated by the explosion remains trapped in the water layer due to the very large acoustic impedance contrasts existing at its upper and lower boundaries. Often the multiple reflections of the explosive pulse are sufficient in amplitude completely to overshadow reflections returning from subsurface strata. (Burg et al., 1951). Other interesting phenomena occur when the bottom is a semi-rigid layer that is thin with respect to seismic wavelengths or when the bottom is tilted with respect to the water surface.

In studying multiple-reflection problems and other aspects of underwater sound propagation, the use of a small-scale model is attractive due to the very high cost of operating a research seismic crew on water and to the relative geometrical simplicity of the problem to be modeled. Such a model was built and is described in the next section. It should be emphasized at the outset that the course of model experiments was planned with the objective of gaining qualitative information about the seismic disturbance under specific field conditions. Physical limitations inherent in the model in many cases precluded the gathering of accurate quantitative data to be compared with theory.

DESCRIPTION OF THE MARINE SEISMIC MODEL

The apparatus used for generating and detecting the model seismic pulses is shown in block diagram form in Figure 1. The sound source in use in the model

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experiments is an underwater spark caused by discharging a 0.5 mfd. capacitor across a 0.001–0.002 inch gap between two 1/16 inch diameter electrodes. With the gap properly adjusted to the above value and with an 1,800-volt charge on the capacitor, the amplitude of the acoustic pulse generated by the spark is found to vary by less than 10 percent. The pressure-vs-time characteristics of the pulse change from spark to spark to a minor degree only.

The receiving element used is a ring-shaped Brush Ceramic A (barium titanate) pressure-sensitive transducer which is radially polarized. Transducers of various sizes have been tested, the element used in the experiments described in

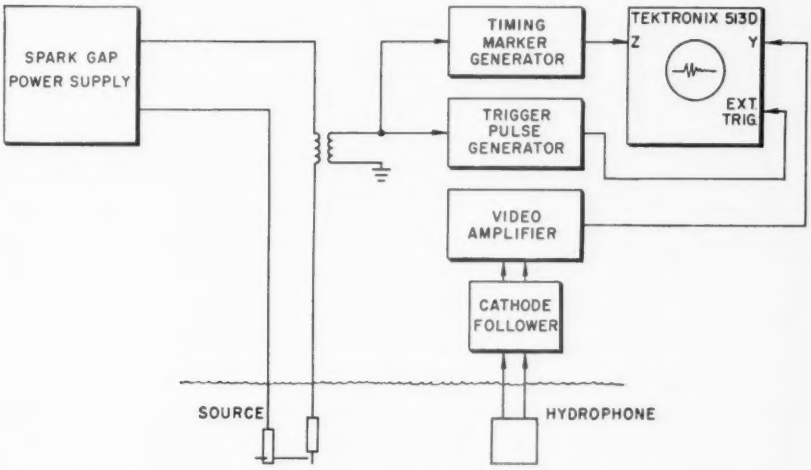

FIG. 1. Block diagram of the marine model.

this paper having a diameter and length of $\frac{1}{4}$ inch and a wall thickness of 0.02 inch. This element is mounted on the end of an eight-inch probe for lowering into the water. The transducer output is fed directly to a cathode follower circuit which serves as an impedance transformer in order to minimize further transmission line losses. The output of the cathode follower is then amplified by a broadband (500 cps to 1 mc) amplifier and fed to the vertical deflection plates of a Tektronix 513D oscilloscope.

A small air-core transformer is connected so that its primary is in series with the spark gap. The current pulse across the gap thus causes a voltage pulse to appear across the secondary of the transformer which is then amplified and shaped. This shaped pulse may be used either to trigger the horizontal sweep of the oscilloscope immediately or can alternatively be used to trigger a phantastron which in turn produces a delayed pulse. The magnitude of this delay is continuously adjustable from 50 to 5,000 microseconds. The delayed pulse may then

be used as a sweep trigger; thus, a later portion of the disturbance can be closely observed. A Polaroid Land Camera is used to make model seismic records.

The original sync pulse is also used to trigger a gate pulse generator which turns on a 20 KC oscillator for approximately 7,000 microseconds. The output of this oscillator goes through a frequency-multiplying and wave-shaping process which produces a series of narrow, large-amplitude pulses with a repetition rate of 200 K pulses per second. To this pulse train a series of pulses with a repetition rate of 20 K p.p.s. derived from the gated oscillator is added with the result that every tenth pulse in the train is of greater amplitude than the rest. When this sequence of pulses is applied to the Z-axis of the oscilloscope and a sweep trigger is supplied, the resulting display is a series of dots 5 microseconds apart which

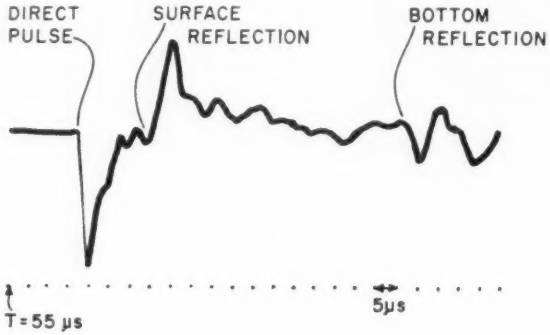

FIG. 2. Simple model record showing direct pulse and reflections from surface and bottom of water layer.

begins at the time of the spark. Since every tenth spot is brighter than the rest long time intervals may be measured quickly and easily.

The spark and hydrophone are mounted in a 30 inch × 90 inch × 30 inch steel tank. When the elements are placed in positions on the long axis of the tank, no boundary reflections arrive for more than 500 microseconds after the spark discharge. This value may be increased to over 1,500 microseconds if small angle-shaped metal baffles are placed at the side walls in proper geometrical relationships to the spark and hydrophone. This value of 1,500 microseconds was sufficient to ensure that no reflections from the tank boundaries could arrive in time to alter significantly the results of the experiments scheduled.

Figure 2 shows a simple model record made with the equipment. The sweep was initiated at a time 55 microseconds after the spark. The first event on the trace is the direct pulse or shock wave. It may be characterized as having an abrupt rise and a considerably slower decay, which may be approximated by an exponential function of the form e^{-Kt}. Arrivals of the reflection of the pulse from the surface and from the steel bottom are also shown. The reversed polarity of

the reflection from the surface indicates a change of character of the pulse from one of compression to one of rarefaction at the comparatively free water-air interface. The polarity of the pulse reflected by the semi-rigid steel bottom, on the other hand, is of the same polarity as the direct pulse.

DISCUSSION OF EXPERIMENTAL RESULTS

Explosion Bubble Pulses

When a charge is detonated under water, a bubble is formed by the burning gases of the explosive. The pressure inside the bubble quickly reaches a value higher than that of the surrounding water and the pressure forces the water away from the center of the bubble in all directions. The enlargement of the bubble and the accompanying decline of the gas pressure in it progress beyond the point of equalization between the pressure in the gas bubble and in the surrounding water due to the inertia of the water as it recedes from the bubble center. However, the pressure inequality that develops finally halts the expansion and causes a contraction to begin. This contraction also continues beyond the point of pressure equilibrium due to the inertia of the water surrounding the bubble and consequently a small high-pressure bubble is developed and another cycle of pulsation is ready to begin. Successive pulses are of smaller amplitude and the bubble finally floats freely to the surface (Cole, 1948).

The existence of this phenomenon of bubble oscillation is of great importance in seismic prospecting since the first of the expansion bubble pulses may cause a shock wave in the water with an amplitude of over half that of the explosion-generated wave. The portion of the seismic record following the arrival of the first bubble pulse is greatly complicated since it must be interpreted as the result of two explosions separated by a considerable time lag. Consequently, the practice generally followed in marine prospecting is to detonate the charge close enough to the surface to make sure that the bubble boundary reaches it during its initial explosion with the result that the gases in the bubble escape the water layer.

Using a spark gap of 0.002 inch and a capacitor voltage of 1,800, as many as four bubble pulses were observed after each spark discharge. Under these conditions, the interval between successive pulses was approximately 550 microseconds; this varied slightly from one spark discharge to another. This interval was also found to decrease as the explosion strength was decreased (by lowering the spark discharge voltage).

Tests were conducted to determine whether a pocket of air could be trapped near enough to the spark gap to result in the relief of the pressure inside the bubble during its first expansion. Figure 3a shows a model record taken with the time scale and amplitude controls set at values to afford a comparison between the direct pulse and first bubble pulse. With the elements in the same positions as for the trace in Figure 3a, a section of $\frac{1}{4}$ inch diameter tubing one inch long with a wall thickness of approximately 0.004 inch was capped at one end and lowered open-end-downward into the water until it rested immediately above the spark.

The resulting trace is shown in Figure 3b. Note that whereas the explosive pulse amplitude is reduced by only about 5 db, the first bubble pulse is attenuated so much as to render it nearly indistinguishable. The method does operate to reduce greatly the ratio between the amplitudes of the explosive and bubble pulses; however, the tremendous buoyancy of an air pocket of the required size would probably prove a barrier to the use of this method in actual marine prospecting.

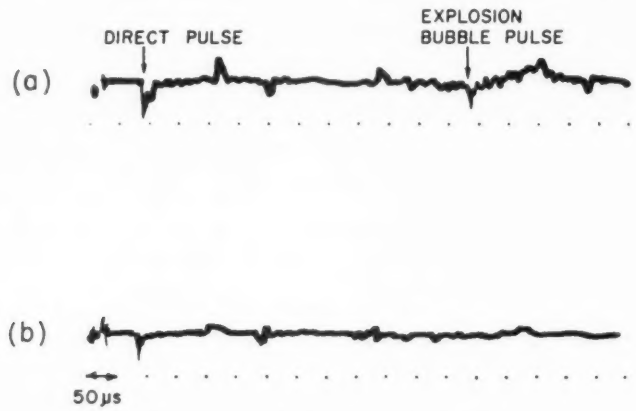

FIG. 3*a*. Comparison of direct and explosion bubble pulses.
FIG. 3*b*. Trace showing attenuation of bubble pulse.

Multiple Reflections

As mentioned early in this article, the multiple-reflection problem frequently makes it difficult to obtain good seismic records in areas in which the water layer is shallow and overlies a semi-rigid bottom. Several theoretical investigations are of interest in connection with this phenomenon (Pekeris, 1948; Press and Ewing, 1950; Burg et al., 1951). One feature of many seismic records made in multiple-reflection areas is that the disturbance as recorded is often remarkably pure in frequency content, sometimes being substantially a sine wave (Burg et al., 1951). The periods of these frequency components seem to bear a direct relationship to the water depth.

If certain assumptions are made regarding the locations of the shot and detector in the water layer and also regarding the pressure pulse originating at the shot, the pressure at the detector may be computed as a function of time after the shot. It will be found that the energy arrivals at the detector form a recurring pattern whose period increases asymptotically to the value $4H/C$ where H is the depth of the water layer and C is the velocity of sound in water. In many seismic problems, the period of recurrence is substantially constant after about one-half second after the shot. Furthermore, if the coefficient of reflection at the ocean floor is high, the amplitudes of successive arrivals decay only slightly during the later

sections of the record. If the two above conditions hold, the pattern may be regarded as quasi-stable and may be approximated theoretically by a stable one. A Fourier analysis of this theoretical approximation gives as its frequency components a harmonic series whose fundamental is $C/4H$. The amplitudes and phases of the harmonics depend on the characteristics of the pressure pulse emitted by the shot and the geometry of the problem. Clearly, if the above parameters are such as to result in frequency components of large amplitude in the seismic range, the recorded trace might be quite pure in frequency content.

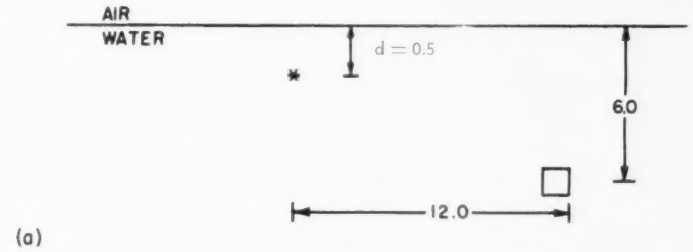

FIG. 4*a*. Geometry used to show effect of spark placement on pulse shape.
FIG. 4*b*. Model record showing waveshape of arrival with geometry as in (*a*).

In most marine prospecting the shot is fired near the surface with a resulting alteration of the pressure pulse arriving at a detector deep within the water layer. To see the effects of a similar placement of the spark in the model, the spark was fixed 0.5 cm below the surface of the water as is indicated in Figure 4a. The waveshape of the pulse received at the detector is shown in Figure 4b. Comparison of this pulse with the direct pulse shown in Figure 2 (where the spark was considerably below the surface of the water) indicates that the pulse with the spark near the surface is merely a superposition of two out-of-phase single-polarity pulses separated by a time delay which increases with the depth of the spark.

It is definitely advisable to point out at this time a discrepancy between the

spark pulse observed in the model and the pressure pulse generated by a seismic shot. Experimental data available (Cole, 1948) suggests that a seismic charge may generate a shock wave with a rise time of less than 0.1 millisecond. Assuming a 1:1,000 time relationship between the model and actual marine problems, the spark pulse should have a rise time of 0.1 microsecond or less; however, as seen in Figure 2, a rise time of approximately 3 microseconds is observed in the electrical output of the detector. Whether this is primarily due to a slow-burning spark or to a limited high-frequency response of the hydrophone is uncertain; it must be

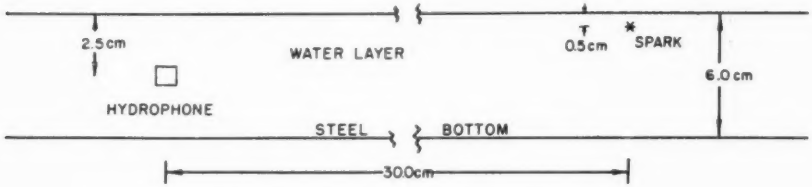

FIG. 5. Geometry used in multiple-reflection experiment.

considered a system characteristic of the model. The primary effect of this discrepancy is to make the shapes of the individual pulses in a train of multiple reflections considerably different from what simple theory would predict if the observed spark pulse had an essentially discontinuous rise. This discrepancy should be kept in mind while making any comparisons between the frequency components observed in the model pulse train and frequencies found on seismic multiple-reflection records.

Figure 5 shows a model set-up suitable for a display of a long train of multiple reflections. There are many possible ray paths from the source to the hydrophone, but they may readily be put in order of increasing length (Burg, et al., 1951), and thus the pressure-vs-time conditions at the detector may be predicted. Since the spark is quite close to the surface, each individual pulse in the train will interfere with a pulse traveling a path of only slightly different length to form a pulse with a shape like the one in Figure 4b. Considering each of these "paired" pulses as a single pulse, the arrival times shown in Table I may be predicted. A value of 1.46×10^5 cm/sec is assumed for the velocity of sound in water.

Next, the model record shown in Figure 6 was made on which the individual pulses in the train of multiple reflections are marked. (The first visible event *R* on the trace has traveled via a refractive path along the steel bottom, probably in the form of a Rayleigh wave. The compressional wave refracted along the bottom is of too low amplitude to be seen here.) Some observations may be made concerning the trace:

1. In general the pulses are of the form shown in Figure 4b.
2. The decay in the amplitudes of the pulses in the later sections of the trace is slow.

TABLE I

Arrival	Polarity	Travel Path, cm.	Arrival Time in μsec.
1	−	30.1	206
2	−	31.3	214
3	+	33.1	227
4	+	36.7	251
5	−	39.6	271
6	−	44.6	305
7	+	48.4	332
8	+	54.0	370
9	−	58.4	400
10	−	64.4	441
11	+	68.8	471
12	+	75.2	515
13	−	79.8	547
14	−	86.4	592
15	+	91.1	624
16	+	97.7	669
17	−	102.5	702

3. The pulses in the train tend to spread somewhat with time. This is due to the fact that the difference between the travel paths of the two pulses making up each doublet in the pulse train increases with increasing path length, approaching a value of twice the spark depth *d*.
4. The model pulse train is such that the waveshapes of the individual pulses, and not their fundamental period of recurrence, primarily determine the predominant frequencies seen in the trace by an observer.

Thus it has been demonstrated that a multiple-reflection train with a period of recurrence dependent on the water depth can be observed in the model. It would be well, however, to take great care in applying conclusions based on the results of this experiment to marine seismic problems since the waveshapes of the individual pulses in the electrical output of the detector are at variance with known data about explosion-generated shock waves in the sea.

Special Multiple-Reflection Problems

Thin Bottom Layer.—In certain areas of the Persian Gulf, multiple-reflection patterns have been noted that are difficult to explain frequency-wise as dependent on the water depth. The ocean floor in some of these cases is of a peculiar composition—a thin layer of limestone overlying a soft, low-velocity zone which in turn is underlain by a hard rock layer at an unknown depth.

FIG. 6. Multiple-reflection record.

The plane wave coefficient of reflection at the boundary between two semi-infinite media is determined entirely by their respective density and velocity constants. However, if one of the media has a thickness on the order of a wavelength of the sound or less, the reflection coefficient changes rapidly with a change in the ratio of thickness to wavelength. Rayleigh gives the following expression for the effective reflection coefficient at the boundary of a plate of finite thickness, immersed in an infinite medium.

$$R_e = \frac{\rho_1 c_1/\rho_2 c_2 - \rho_2 c_2/\rho_1 c_1}{\sqrt{4\cot^2(2\pi l/\lambda) + (\rho_1 c_1/\rho_2 c_2 + \rho_2 c_2/\rho_1 c_1)^2}}$$

where

R_e = ratio of reflected to incident amplitudes,
$\rho_1 c_1$ = acoustic resistance of the plate,
$\rho_2 c_2$ = acoustic resistance of the medium,
λ = wavelength of sound in the plate, and
l = thickness of the plate.

It may be seen that $R_e = 0$ when $2\pi l/\lambda = 0, \pi, 2\pi$, etc., due to the behavior of the $\cot^2$ term at these values. From the above, it may be apparent that if we select a plate with a properly low $2\pi l/\lambda$ ratio, that is, a properly thin one, that plate might perform a frequency-selective filtering operation on a pulse of broad spectrum striking it. It might transmit proportionately more of the lower frequency components of the pulse while reflecting more of the components of higher frequency.

To demonstrate this in a crude qualitative manner, an experiment was performed in which the geometry of Figure 7a was used. Two thin steel plates were made for use in the experiment with thicknesses of 0.018 inch and 0.0375 inch. Since the major part of the frequency spectrum of the spark pulse was in the range 20 KC–200 KC the $2\pi l/\lambda$ ratios relating plate thickness to frequency fell in the range from 0.01 to 0.25.

The results of the experiment are shown in Figures 7b, c, and d. The trace in Figure 7b serves as a reference, showing the waveshape of the pulse reflected from the tank bottom with the elements 9.0 cm apart and 4.0 cm above it. The reflected pulse, evident at about one hundred microseconds on the record, contains a wide band of frequencies. Figures 6c and 6d show the result when the plates, 0.018 and 0.0375 inches thick respectively, were used as reflectors as is shown in the diagram in Figure 7a. Two reflected pulses are evident on each of these records. The first of these occurs at 107 microseconds and represents that portion of the spark pulse reflected at the surface of the thin plate while the second pulse, occurring at 135 microseconds, represents energy that has passed through the plate, been reflected upward at the steel bottom, and returned to the hydrophone, again passing through the plate.

A comparison of Figures 7c and 7d shows that the 0.018 inch plate passed

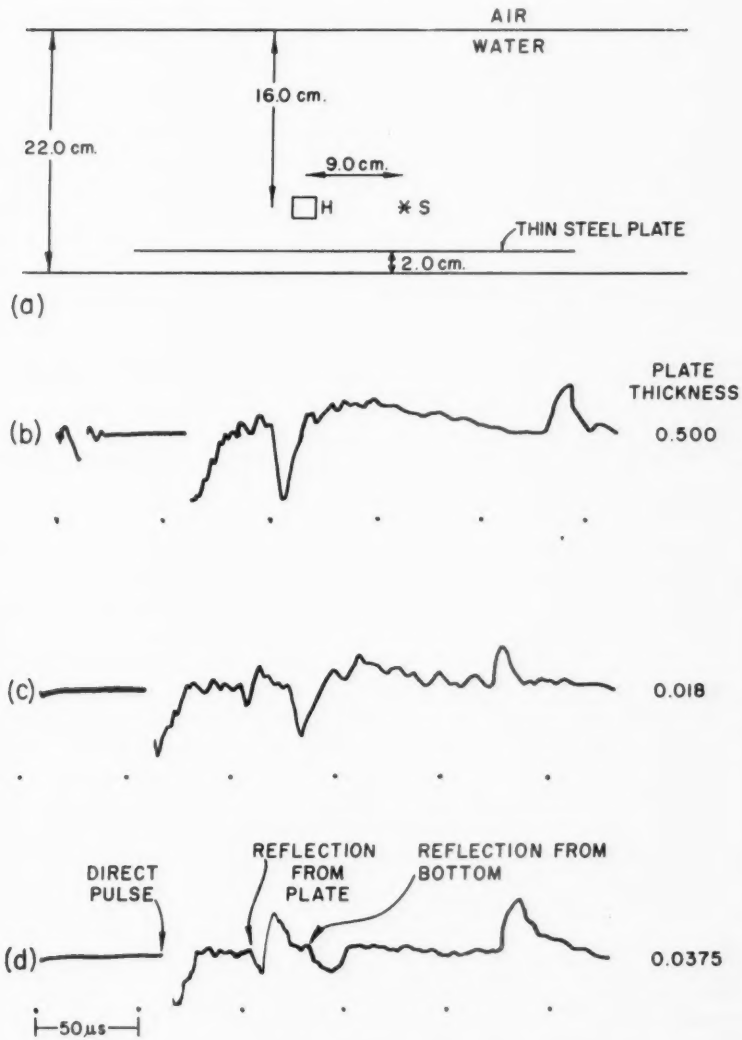

FIG. 7. Model records showing the effect of thickness of reflector on reflection character.

more high-frequency energy than did the 0.0375 inch plate. This may be ascertained by comparing the waveshapes of the events at 135 microseconds on the two records which are due, as outlined previously, to energy that has passed twice through the plates. Thus, it has been shown qualitatively that the two plates op-

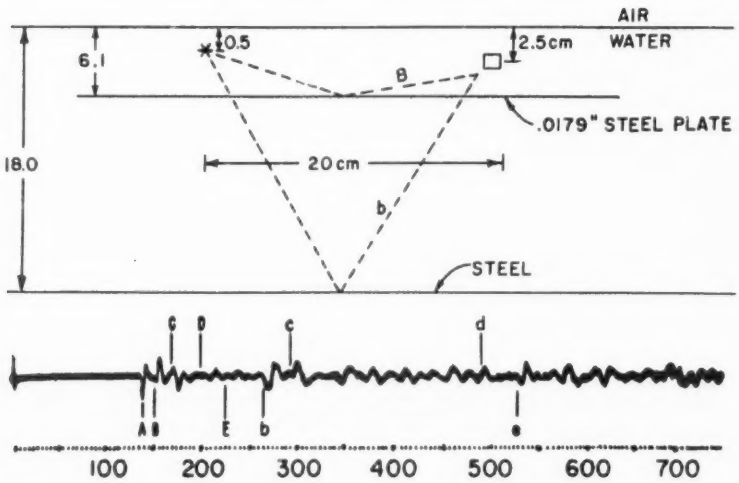

FIG. 8. Multiple-reflection pattern with a thin horizontal plate within the water layer.

erate selectively on the spark pulse to the extent of transmitting more of the lower frequencies in it while reflecting more of the higher frequencies.

The preceding experiment, which showed how the explosive pulse might be partially reflected at the surface of the thin steel plate, suggested the following possibility. If the bottom of the water layer in a multiple-reflection case was so thin as to be accoustically semi-transparent and if the soft zone beneath the ocean floor had acoustic properties similar to those of water, might it not be possible that an observed multiple-reflection pattern might be partially due to reflections between the surface of the water layer and a massive rock layer lying at some distance beneath the ocean floor? To investigate this possibility, the geometry shown in Figure 8a was set up and the lengths of the possible energy travel paths shown in Table II below were computed. The paths are arranged in order of increasing length and are also divided into two groups, one corresponding to

TABLE II

Ray	Polarity	Travel Path, cm.	Arrival Time in μsec.
A	−	20.1	138
B	−	22.0	151
C	+	24.6	168
D	+	29.2	200
E	−	33.0	226
a (same as A)	−	20.1	138
b	−	38.6	264
c	+	43.0	295
d	+	71.8	492
e	−	76.6	525

reflections between the surface of the water and the thin plate, and the other pertaining to reflections between the surface and the permanent bottom. The ray paths in the former group are designated by capital letters while lower case letters are used for the rays in the latter group.

The model seismic record made under the conditions of Figure 8a is shown in Figure 8b. On it are marked the events corresponding to the ray paths in the table above. It will be noted that the amplitudes of the events in the first series die out fairly rapidly. This is due to the comparatively low effective coefficient of reflection at the surface of the 0.018 inch plate. Furthermore, the waveshapes of the individual pulses in the first series differ from those observed in the simple multiple-reflection case of Figure 5 in that the second lobe of the pulse is of greater amplitude than the first. This is caused by the difference in waveshape between the pulse reflected at the steel bottom of the model (Figure 2) and the pulse reflected at the surface of a thin steel plate (Figures 7b and 7c).

Thus it has been shown with the model that two separate multiple-reflection trains may be evident on a record, only one of which can be analyzed using an observation of the water depth. Furthermore, complex travel paths may result which involve rays reflected at the massive bottom which then ascend into the upper water layer and are multiply reflected at the water surface and the thin bottom. It may be pointed out that in the previous experiment the more prominent, slowly-decaying pulse series could not be analyzed using a simple observation of the water depth.

Tilted Bottom Layer.—In the special case in which the bottom of the water layer is tilted slightly with respect to its surface, the multiple-reflection pattern is somewhat altered. Consider the case of multiple reflections between two infinite *parallel* interfaces enclosing a homogenous medium. These conditions hold true about the ray paths along which energy must propagate from source to receiver:

1. A ray striking an interface with an angle θ from normal incidence will be multiply reflected an infinite number of times from the interfaces and will make an angle of θ from normal incidence at each reflection.
2. If n is a positive integer, there is a multiply reflected ray from source to receiver which undergoes n and only n reflections.
3. If L is any number whatsoever, there is a multiply reflected ray from source to receiver of length L or greater.

None of the above conditions hold true if the bottom interface is tilted; why this is true is indicated in Figure 9. Figure 9a shows two possible ray paths along which energy may propagate from source to receiver. The dotted ray proceeds downslope from source to receiver while the heavily drawn ray begins its journey *away* from the hydrophone; after a number of reflections the ray turns back on itself and proceeds to the hydrophone.

Consider a ray of the first type incident on the surface at an angle θ and propagated toward deeper water. As is seen in Figure 8b, successive reflections alter the direction of the ray in a manner to make it tend toward a direction more or less parallel with the boundaries of the water layer. Next, consider the second

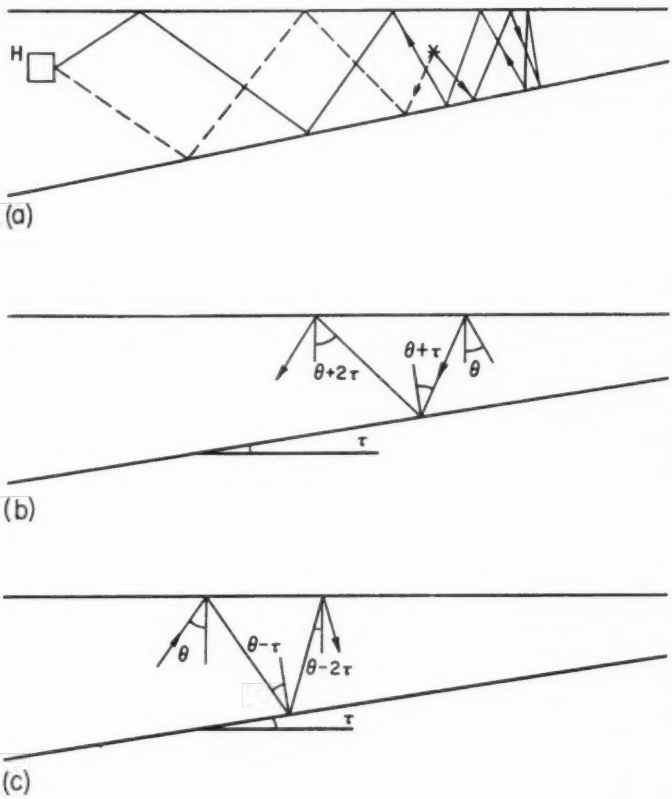

FIG. 9. Effect of two non-parallel interfaces on a multiply reflected ray.

case in which a ray is propagated toward shallower water. In this case, successive reflections tend to make the ray strike the interfaces more nearly perpendicularly.

The changes in angles of incidence that a multiply reflected ray from the source to detector undergoes in this case means that there is a maximum number of reflections that a ray may undergo at the tilted interface. This maximum number may be computed to be the greatest integer n such that $n\tau < 90°$, if one makes the approximation that the source and receiver are located at the horizontal interface. Poulter (1950) has derived an expression for the path length corresponding to a given multiple reflection number under these conditions:

$$A_h = \sqrt{A_0^2 + 4rr' \sin h\tau}$$

where

A_0 = separation between source and detector,
r = normal distance from shot point to vertex line between the interfaces,
r' = normal distance from detector to vertex line between the interfaces,
h = number of reflections at tilted interface, and
τ = angle of tilt of tilted interface.

The fact that no ray from source to detector may undergo more than $90/\tau$ reflections at the tilted interface means that no multiply reflected pulse will be received at a time later than that corresponding to the travel path corresponding to the maximum reflection number. Thus, the multiple-reflection pattern will terminate at a time t which is predictable from a knowledge of the geometry of the problem.

To demonstrate this phenomenon, the elements of the model were arranged as shown in the diagram in Figure 10a. Under these conditions, the maximum number of reflections that a ray could undergo at the tilted interface was equal to 12. The corresponding path length may be computed, using $A_0 = 7.0$ cm, $r = 18.5$ cm, $r' = 11.5$ cm. $\tau = 7.167°$, and $h = 12$:

$$A_{12} = \sqrt{49 + 4(18.5)(11.5)\sin^2 12(7.167°)}$$

$$A_{12} = 29.9 \text{ cm}$$

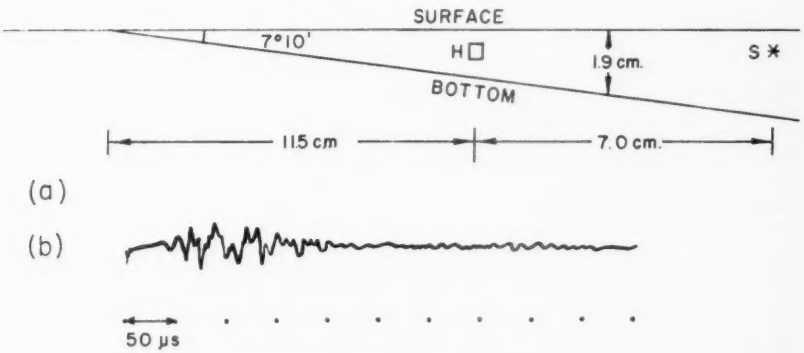

FIG. 10. Multiple reflections in a wedge shaped water layer.

Using for the velocity of sound in water a value of 1.46×10^5 cm/sec, the corresponding travel time is 205 microseconds. Thus, under the geometrical conditions of Figure 10a, no multiple reflections should arrive at the detector later than 205 microseconds. The trace shown in Figure 10b shows the disturbance created under these conditions. The multiple reflections terminate as predicted at approximately 200 microseconds.

Methods of Attenuating Multiple Reflections

Two methods of eliminating or attenuating multiple reflections are:

1. One which involves alteration of the water layer to diminish the amplitude of the disturbance at the detector, and
2. One which involves treatment of the voltage wave in the amplifier to remove the portions of it due to the multiple reflections.

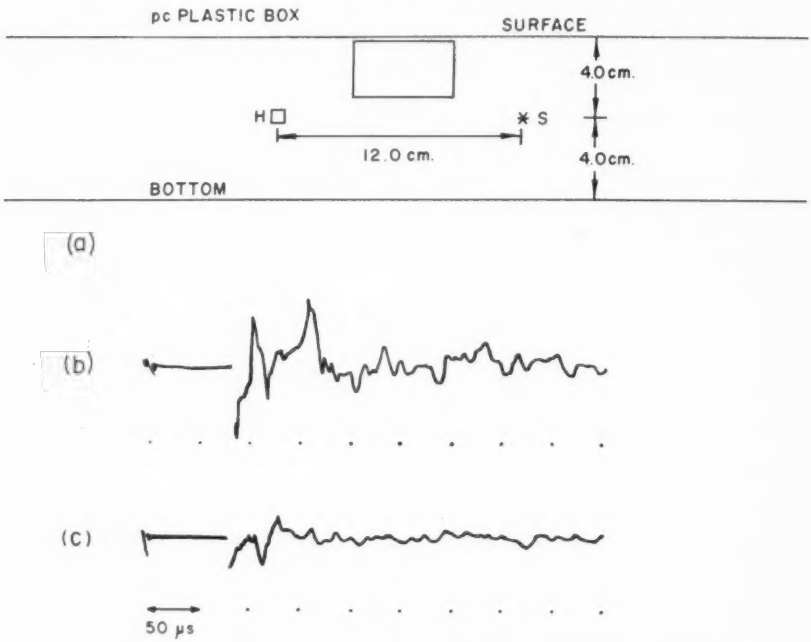

FIG. 11. Model records showing the effect of a mass of air bubbles on a multiple-reflection pattern.

One experiment was performed which made use of the first method to attenuate the reflections. A small box was constructed from some 0.010 inch thick plastic whose ρc was approximately the same as that of water. Tests indicated that the box had essentially no attenuating effect on a spark pulse passing through it. This box was submerged until its open top was a few millimeters below the surface of the water as is shown in Figure 11a. The record of the disturbance (Figure 11b) shows several reflections from the surface and bottom of the water layer. Next, some effervescent powder was placed in the box and another record was made (Figure 11c). The bubble layer at the surface of the water in this case greatly damped the first few reflections. From this it would seem that if a bubble layer of sufficient extent could be created in a marine seismic problem, a considerable attenuation of the multiple reflections would occur.

One possible application of the latter of the two methods outlined above would involve the use of a "notch" filter with the notch in its transfer characteristic at the same value as the predominant multiple-reflection frequency. The location of the notch should be variable in quite small increments to allow for correspondingly small changes in water depth and multiple-reflection frequencies. The effectiveness of this method will be evaluated in a future series of experiments with the model.

Possible Applications of the Marine Model

Solid Model Problems.—A marine model may be used advantageously to investigate certain special cases encountered in prospecting on land, provided care is taken in the interpretation of the results. In a model study of the effects on seismic signals of inhomogeneities of comparatively small size in the weathered layer near the detector, the use of water as a model medium is fairly attractive for two reasons. First, the complete lack of rigidity of water makes it possible to conduct experiments involving the placing of inhomogeneities within the model medium with no difficulty at all, as contrasted with the solid model case in which it is necessary to construct substantially a new model whenever it is desired to change the size, shape, or location of the inhomogeneities. Second, the contrast between the acoustic properties of solids in general and water is somewhat mitigated by the fact that the weathered layer, where many inhomogeneties and sharp discontinuities are found, has a considerably lower sound velocity and modulus of rigidity than do many solids; e.g., deep-lying limestones. Two seismic problems currently under study concern the effects on the seismic wave of a caverned rock layer and seismic wave transmission phenomena in the vicinity of a fault.

SOME LIMITATIONS OF THE MARINE MODEL

Limitations in a seismic model arise when there is an imperfect analogue between some component of the model and its counterpart in the fields. These limitations may arise from differences between the acoustical properties or geometrical characteristics of the model structure and those of the actual field structure. They may also arise from any disparity in size or performance between the model source and detector and those used in the field other than the disparities inherent in the constant scale factor. Obviously there are many departures from a perfect analogy in the best of models and clearly some of these departures prove to be serious while others are quite trivial.

There were two limiting factors that caused difficulty in the course of experimentation with the marine model. One concerned the rise time of the pulse emitted by the source as received by the hydrophone, which was not short enough. As was outlined early in this article, this rendered impossible a faithful model representation of the sequence of short, sharp pulses that theory predicted in a multiple-reflection problem. As was mentioned previously, this could be caused either by an imperfect analogue between the frequency components present in

the spark pulse and those present in the shock wave produced by a marine seismic charge, or by a poor high-frequency response of the hydrophone.

Another significant limitation of the marine model concerned the size of the hydrophone which is quite large considering the model scale. This made difficult an accurate observation of the disturbance in the immediate vicinity of an acoustic discontinuity.

ACKNOWLEDGMENTS

The author began his course of experimentation with what was in fact a completed model. He wishes to express his appreciation of the work done by Donald R. Dubbert, who designed and constructed most of the electronic gear in the system, and by Forrest West, who designed the spark-gap power supply and all the mechanical elements of the system. He also wishes to express his appreciation for the guidance of Dr. Hal J. Jones, Director of Geophysical Research, who suggested many of the model experiments that have been performed.

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NOISE ANALYSIS AND MULTIPLE SEISMOMETER THEORY*

MARK K. SMITH†

ABSTRACT

The purpose of this paper is to present a general theory and some techniques for analyzing, estimating, and displaying the characteristics of wave noise, random noise, and reflection signal, in a form convenient for designing and evaluating multiple seismometer arrays and filters. Modifications of the characteristics resulting from weathering and elevation variations, and modifications of the array responses resulting from variations in plant and seismometer spacing are discussed. Criteria for the design of arrays are presented along with a multiple seismometer nomogram based on a specific set of criteria.

INTRODUCTION

Many papers on the subject of multiple seismometer arrays have been published in the past twenty years. Various authors have based their treatments on antenna theory (Johnson, 1939; Hales and Edwards, 1955), statistics (Klipsch, 1936) and empirical results. Some papers have included both statistics and antenna theory (Lombardi, 1955) but in general, the theoretical treatments have been based on restrictive assumptions about the nature of the signal and the noise. For example, antenna theory approaches require the assumption of plane wave propagation and are often restricted to the steady state. Statistical approaches involve the assumption of "white light" random noise and plane wave signal with vertical incidence. Both approaches often neglect the effect on the signal of normal moveout and dip, and weathering and elevation variations across the group.

In this paper we present a treatment based on the theory of Generalized Harmonic Analysis (Wiener, 1933), and initially requiring no restrictive assumptions as to the nature of the signal or the noise. This treatment was motivated by the need for a convenient method of analyzing noise studies with the objective of determining the optimum recording system consisting of best filter setting, multiple seismometer array, multiple shot array, shot depth and offset distance. However, the emphasis of the present paper will be on determining the best multiple seismometer geometry in a configuration restricted to a single line of seismometers in line with the shot hole. Also, since routine operations often preclude a complete noise analysis, "best" estimates of the signal and noise are used to derive a multiple seismometer nomogram for field application.

APPLICATION OF THE FOURIER TRANSFORM IN TWO VARIABLES[1]

Let us define $F_{11}(x, t)$ as the output of a single seismometer and linear ampli-

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[1] For another application of the Fourier Transform in two variables to geophysical problems see Swartz (1954).

fier at time t and position x on a surface line passing through the shot hole. Considering the physical behavior of $F_{11}(x, t)$, we can then write

$$F_{11}(x, t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F_{22}(k, f)e^{j2\pi(ft-kx)}dkdf \tag{1}$$

and

$$F_{22}(k, f) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F_{11}(x, t)e^{-j2\pi(ft-kx)}dxdt, \tag{2}$$

where $F_{22}(k, f)$ will be called the double spectrum of $F_{11}(x, t)$, f is frequency and k will be designated as wave number. This differs from the conventional usage of the term wave number by a factor of 2π.

Effect of Multiple Seismometers and Filtering

If we now add the weighted outputs of n seismometers along the line x, we can write the multiple array output as a function of time t and location x as

$$\sum_{i=1}^{n} H_1^*(i)F_{11}(x + \xi_i, t), \tag{3}$$

where $H_1^*(i)$ is the weighting factor of the ith seismometer and ξ_i is the distance from some point x within the group to the ith seismometer measured positive away from the origin $x=0$, and negative towards the origin. If in addition we pass this multiple seismometer output through a filter with impulse response $H_1(t)$, and designate the filtered output as $G_{11}(x, t)$, we can write

$$G_{11}(x, t) = \int_{-\infty}^{\infty} H_1(\tau) \sum_{i=1}^{n} H_1^*(i)F_{11}(x + \xi_i, t - \tau)d\tau. \tag{4}$$

Letting $t_1=t-\tau$ and $x_1=x+\xi_i$, the double spectrum of $G_{11}(x, t)$ can be written as

$$\begin{aligned} G_{22}(k, f) = \sum_{i=1}^{n} H_1^*(i)e^{-j2\pi k\xi_i} \int_{-\infty}^{\infty} H_1(\tau)e^{-j2\pi f\tau} \\ d\tau \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F_{11}(x_1, t_1)e^{-j2\pi(ft_1-kx_1)}dx_1dt_1. \end{aligned} \tag{5}$$

Thus if we write

$$H_2^*(k) = \sum_{i=1}^{n} H_1^*(i)e^{-j2\pi k\xi_i}, \tag{6}$$

and

$$H_2(f) = \int_{-\infty}^{\infty} H_1(\tau)e^{-j2\pi if\tau}d\tau, \tag{7}$$

by equations (2), (6), and (7), equation (5) becomes

$$G_{22}(k, f) = H_2^*(k)H_2(f)F_{22}(k, f). \tag{8}$$

Equation (7) is the conventional expression for the complex frequency response of a filter with impulse response $H_1(t)$. Similarly we can define equation (6) as the expression for the complex wave number response of a multiple seismometer array with weighting factors $H_1^*(i)$ and seismometer locations ξ_i. If we call the product $H_2^*(k)H_2(f)$ the system response, then equation (8) gives us an expression for the output spectrum as a product of the input spectrum and the system response. The significance of this expression lies not only in the fact that the system response is independent of the input, but also that no restrictive assumptions about $F_{22}(k, f)$ were necessary in deriving the relationship.

APPLICATION OF THE POWER SPECTRUM IN TWO VARIABLES

For the purpose of considering random noise and random variations in the system response and signal, as well as simplicity in graphical representation, it is convenient to consider the output and input in terms of their power spectra. Thus by multiplying equation (8) by its complex conjugate we obtain the expression

$$|G_{22}(k, f)|^2 = |H_2^*(k)|^2 |H_2(f)|^2 |F_{22}(k, f)|^2, \tag{9}$$

where $|H_2^*(k)|^2 |H_2(f)|^2$ is now the power response of the system and in particular $|H_2(f)|$ is the conventional filter amplitude response. Since the output power spectrum $|G_{22}(k, f)|^2$, the input power spectrum $|F_{22}(k, f)|^2$, and the system power response are all real and positive, we see that these functions can be represented as contours on the k-f plane. Thus, by contouring the system power response we can examine its effect on any input power spectrum or, conversely, given an input power spectrum, we can determine the best system power response. For this purpose it will be necessary to consider the system phase response also.

SYSTEM POWER AND PHASE RESPONSE

The complex frequency response of a filter may be written as

$$H_2(f) = |H_2(f)| e^{j\theta(f)}. \tag{10}$$

Similarly, the complex wave number response of a multiple seismometer array may be written as

$$H_2^*(k) = |H_2^*(k)| e^{j\theta^*(k)}. \tag{11}$$

Thus the system power response is given by

$$|H_2^*(k)|^2 |H_2(f)|^2 = \overline{H_2^*}(k)H_2^*(k)\overline{H_2}(f)H_2(f), \tag{12}$$

where the bar designates the complex conjugate. The system phase response is then

$$\theta(k, f) = \theta^*(k) + \theta(f). \tag{13}$$

Example of System Power Response

If we consider the example of a single line of ten seismometers spaced 20 feet apart, where the response of each seismometer is unity we obtain, using equation (6)

$$H_2^*(k) = \frac{\sin 200\pi k}{\sin 20\pi k}, \tag{14}$$

assuming the center of the group as the x location of the output. This function resembles the familiar antenna theory representation of the multiple seismometer response as a function of reciprocal wave length. The power response of this array will then be

$$| H_2^*(k) |^2 = \frac{\sin^2 200\pi k}{\sin^2 20\pi k} \tag{15}$$

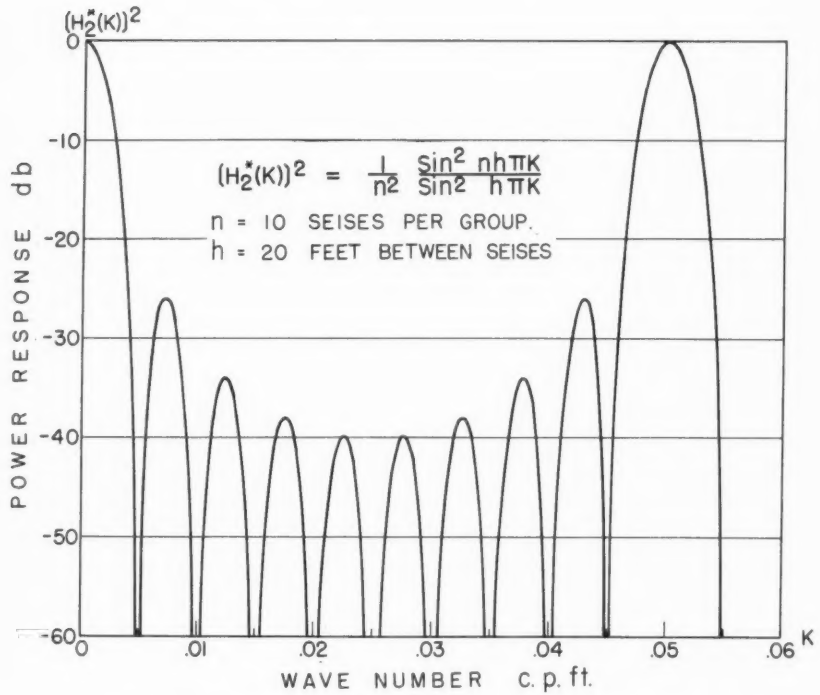

FIG. 1. Multiple seismometer power response as a function of wave number.

as plotted in Figure 1, and the phase response over the plotted interval will be given by

$$\theta^*(k) = \begin{cases} 0 & 2m < \left|\dfrac{k}{200}\right| < 2m + 1, \\ \pi & 2m + 1 < \dfrac{k}{200} < 2m + 2, \end{cases} \qquad m = 0, 1, 2, 3, 4. \quad (16)$$

If we choose as our filter power response the function shown in Figure 2, the contoured system response will be as shown in Figure 3, where the contour lines are in decibels. Thus, for any particular value of k and f the system power response can be determined from the contour plot. For example, an input with a frequency of 60 cps and wave number of .0075 cycles/ft will be reduced in relative power by a factor of 30 db due to the effect of both the multiple seismometers and the filter.

REPRESENTATION OF THE INPUT FUNCTION

If we write the input function $F_{11}(x, t)$ as the sum of two terms,

$$F_{11}(x, t) = S_{11}(x, t) + N_{11}(x, t), \quad (17)$$

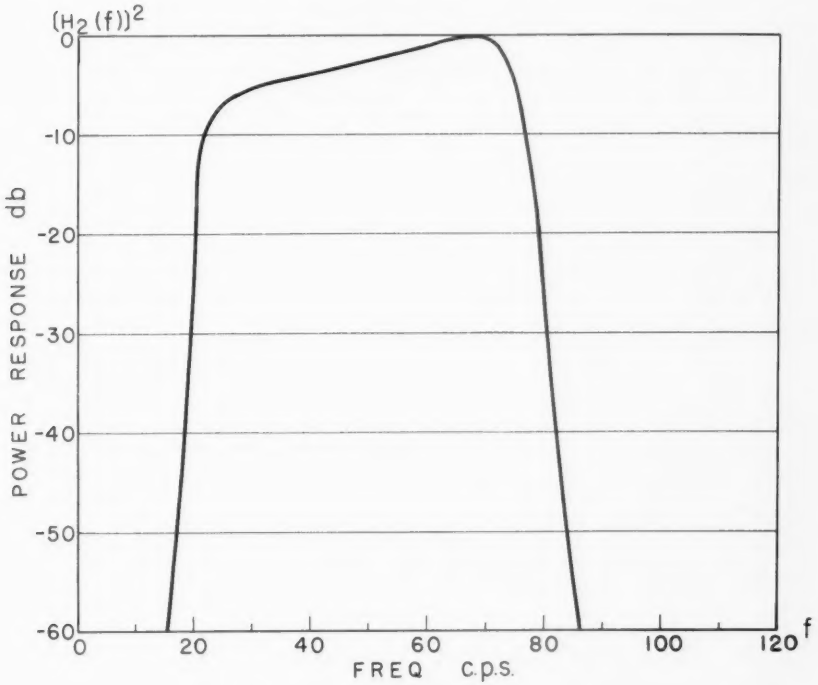

FIG. 2. Filter power response as a function of frequency.

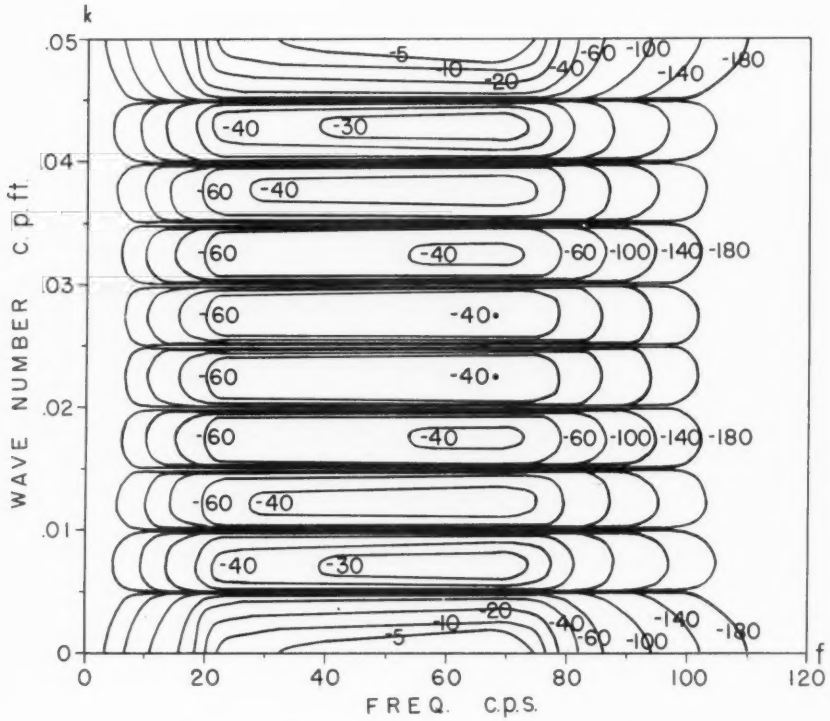

FIG. 3. Combined system power response contoured in db.

where $S_{11}(x, t)$ is the signal and $N_{11}(x, t)$ is the noise, it is not difficult to show that

$$|F_{22}(k, f)|^2 = |S_{22}(k, f)|^2 + |N_{22}(k, f)|^2 + 2[\text{Real Part of } \overline{S_{22}(k, f)} N_{22}(k, f)], \tag{18}$$

where $|S_{22}(k, f)|^2$ is the power spectrum of the signal, $|N_{22}(k, f)|^2$ is the power spectrum of the noise, and $\overline{S_{22}}(k, f)\ N_{22}(k, f)$ is the cross-power spectrum of the signal and noise. These terms can also be written as the transforms of double correlation functions

$$|S_{22}(k, f)|^2 = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \phi_{SS}(\xi, \tau) e^{-i2\pi(f\tau - k\xi)} d\xi d\tau, \tag{19}$$

$$|N_{22}(k, f)|^2 = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \phi_{NN}(\xi, \tau) e^{-i2\pi(f\tau - k\xi)} d\xi d\tau, \tag{20}$$

and

$$\overline{S_{22}}(k, f)N_{22}(k, f) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\phi_{SN}(\xi, \tau)e^{-i2\pi(f\tau-k\xi)}d\xi d\tau, \tag{21}$$

where the double correlation function is defined by

$$\phi_{A,B}(\xi, \tau) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}A_{11}(x, t)B_{11}(x+\xi, t+\tau)dxdt. \tag{22}$$

To illustrate the significance and characteristics of the terms in equation (18), and to illustrate the application of the above equations, let us consider some general examples of signal and noise.

Damped Plane Waves

If the noise (or signal) is a damped plane wave with an apparent velocity c in the x direction,

$$N_{11}(x, t) = D_{11}(x)P_{11}\left(t - \frac{x}{c}\right),^{2}$$

it is shown in the Appendix that

$$|N_{22}(k, f)|^2 = \left|D_{22}\left(\frac{f}{c} - k\right)\right|^2 |P_{22}(f)|^2, \tag{23}$$

where $|P_{22}(f)|$ is the frequency amplitude spectrum of the plane wave and $|D_{22}((f/c)-k)|^2$ is the power spectrum of the damping function D_{11}, or the damping characteristic. In particular, if $D_{11}(x)$ is a constant (no damping),

$$\left|D_{22}\left(\frac{f}{c} - k\right)\right|^2 = \delta\left(\frac{f}{c} - k\right)$$

where

$$\delta\left(\frac{f}{c} - k\right) = \begin{cases} 0 & \dfrac{f}{c} \neq k \\ \infty & \dfrac{f}{c} = k. \end{cases} \tag{24}$$

Thus the contours of $\delta[(f/c)-k]$ lie on top of one another forming a line on the k-f plot, with slope $1/c$, which passes through the origin. If instead, the damping function is $D_{11}(x) = 1/\sqrt{|x|}$, we find that

[2] The damping factor $D_{11}(x)$ is introduced to satisfy the convergence requirements on the integrals. Clearly, by letting $D_{11}(x)$ approach unity we can achieve any desired degree of persistence. It is also assumed that $P_{11}(u)$ damps as $|u| \to \infty$.

$$\left| D_{22}\left(\frac{f}{c} - k\right)\right|^2 = \frac{1}{\left|\frac{f}{c} - k\right|}. \tag{25}$$

In any case, the contours of $|D_{22}((f/c)-k)|^2$ alone, are the lines $|(f/c)-k| = \text{constant}$. However, the contours of $|N_{22}(k, f)|^2$ will be modified by the function $|P_{22}(f)|^2$.

Further, if the noise is a damped dispersive plane wave, we find that

$$|N_{22}(k, f)|^2 = \left| D_{22}\left(\frac{f}{c(f)} - k\right)\right|^2 |P_{22}(f)|^2, \tag{26}$$

where the velocity $c(f)$ is a function of frequency. Thus, the damping characteristic contours are curves in the k-f plane.

"Random" Noise

Our definition of random noise will be non-rigorous. However, for practical purposes this approach offers certain advantages. First, we wish to illustrate the significance of our concept of random noise, and secondly, to show that the cross-power spectrum terms involving "random" noise can be neglected in our analysis.

Thus far we have investigated certain well-defined noise waves. In addition to these waves, however, the noise will be composed of an infinite variety of "waves" with different apparent velocities, different frequency contents, different phases, and different modes of vibration. The superposition of this infinity of "waves" we choose to call the complex noise $r_{11}(x, t)$. For a given shot the function ${}_i r_{11}(x, t)$ will possess a unique Fourier Transform in two variables ${}_i r_{22}(k, f)$. However, at the next shotpoint we will, in general, find a different spectrum. We will therefore consider the functions ${}_i r_{22}(k, f)$ to be random in i. Since our objective is to obtain an estimate of the noise over an entire area, and thus determine the best filter setting and multiple seismometer array for the entire area, we are interested in the average characteristics of the ${}_i r_{22}(k, f)$'s. Now we can write

$${}_i r_{22}(k, f) = |{}_i r_{22}(k, f)| e^{j\theta_i(k,f)}, \tag{27}$$

where we will assume that the θ_i's are randomly distributed between 0 and 2π, and that the expected value of $e^{j\theta_i}$ is zero. Then the expected value of ${}_i r_{22}(k, f)$ will also be zero. However, the expected value of ${}_i r_{22}(k, f)\,\overline{{}_i r_{22}}(k, f)$ will be

$$|R_{22}(k, f)|^2 = \frac{1}{A} \sum_i |{}_i r_{22}(k, f)|^2, \tag{28}$$

where A is a normalizing constant. We will call this function the power spectrum of the "random" noise. In particular, if the functions $|{}_i r_{22}(k, f)|^2$ are essentially independent of i, then $|r_{22}(k, f)|^2$ provides a good estimate of $|R_{22}(k, f)|^2$. How-

ever, the phase angles have no significance. It follows from the above statements that the expected value of $\overline{Q}_{22}(k, f)$, $r_{22}(k, f)$ is also zero where $Q_{22}(k, f)$ is any spectrum. Thus, we can neglect the cross-power terms involving "random" noise.

Observations indicate that the function $r_{11}(x, t)$ tends to become less coherent with $r_{11}(x+\xi, t)$ as ξ increases. Therefore, let us investigate the example in which the time cross-correlation function of $r_{11}(x, t)$ and $r_{11}(x+\xi, t)$ is given by

$$\phi_{x, x+\xi}(\tau) = \int_{-\infty}^{\infty} r_{11}(x, t) r_{11}(x+\xi, t+\tau) dt = e^{-2\pi\alpha|\xi|}\phi_x(\tau).^{3} \tag{29}$$

Therefore, in the notation of equation (22)

$$\phi_{rr}(\xi, \tau) = \int_{-\infty}^{\infty} e^{-2\pi\alpha|\xi|}\phi_x(\tau) dx = e^{-2\pi\alpha|\xi|}\phi(\tau), \tag{30}$$

where $\phi(\tau)$ is the average correlation function over all x, and

$$|\, r_{22}(k, f)\,|^2 = \frac{1}{\pi}\int_{-\infty}^{\infty}\phi(\tau)e^{-i2\pi f\tau}d\tau\,\frac{\alpha}{\alpha^2 + k^2}\,. \tag{31}$$

If we let

$$\eta^2(f) = \frac{1}{\pi}\int_{-\infty}^{\infty}\phi(\tau)e^{-i2\pi f\tau}d\tau, \tag{32}$$

and use $|\, r_{22}(k, f)\,|^2$ as the best estimate of the random noise, we get

$$|\, R_{22}(k, f)\,|^2 = \eta^2(f)\,\frac{\alpha}{\alpha^2 + k^2}\,. \tag{33}$$

This function is sketched in Figure 4 for an arbitrarily assumed $\eta^2(f)$ and for a value of $\alpha = .032$. It should be noted that the power spectrum of the random noise extends over the entire k-f plane, and that $|\, R_{22}(k, f)\,|^2$ decreases with increasing k. The slope of this function will decrease with increasing α. Thus, as the noise becomes more random, $\alpha \to \infty$, $|\, R_{22}(k, f)\,|^2$ becomes less dependent on k. Further, as the noise becomes more random with respect to time, $|\, R_{22}(k, f)\,|^2$ becomes lesss dependent on f. Thus in the limit we reach "white light" random noise with $|\, R_{22}(k, f)\,|^2$ constant over the entire k-f plane.

Approximate Power Spectrum of the Input Function

We have considered both wave noise and random noise, and have indicated that the cross-spectrum of random noise and any waves can be neglected. Therefore, if we consider the noise as being composed of both waves and random energy, we can write

[3] Jones and Morrison (1954) have experimentally determined the function $\phi_{x, x+\xi}(0)$ for the Buckner area, Dallas County, Texas. Horton (1955) gives examples of time correlation functions computed from records shot in this area.

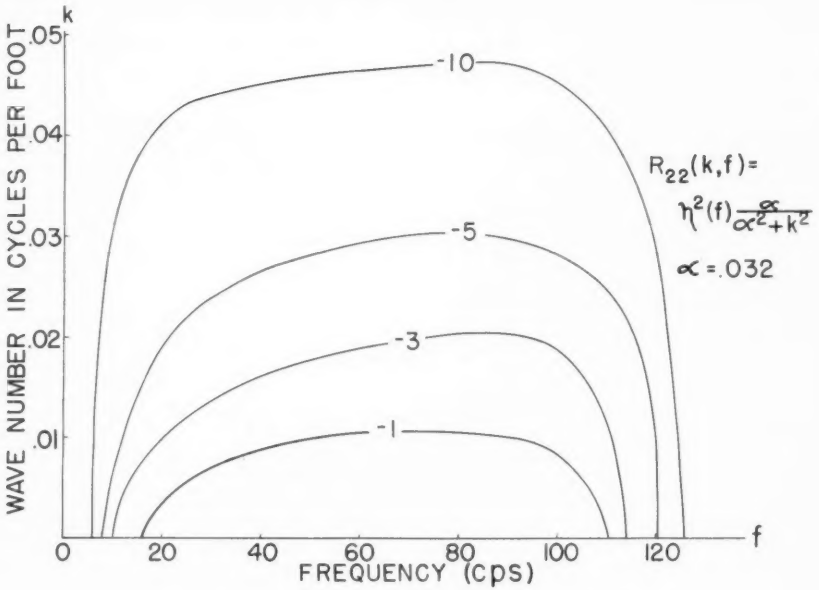

FIG. 4. Double power spectrum representation of random noise.

$$N_{22}(k, f) = W_{22}(k, f) + r_{22}(k, f),$$

where $W_{22}(k, f)$ is the complex spectrum of the waves. Then

$$|N_{22}(k, f)|^2 \simeq |W_{22}(k, f)|^2 + |R_{22}(k, f)|^2.$$

Further, we have shown that the power spectra of the waves reach sharp maxima in the k-f plane on the curves $k=f/c(f)$. Thus, the cross-spectra of these waves will be small if their respective curves $k=f/c(f)$ do not intersect. Thus we can write

$$|F_{22}(k, f)|^2 \simeq |S_{22}(k, f)|^2 + |W_{22}(k, f)|^2 + |R_{22}(k, f)|^2. \qquad (34)$$

Using this same condition we can decompose both $|S_{22}(k, f)|^2$ and $|W_{22}(k, f)|^2$ approximately into sums of the power spectra of individual waves. This approximation is convenient for the experimental determination of the input function.

ESTIMATION OF THE INPUT FUNCTION

Wave Noise and Random Noise

Experimental noise studies often consist of continuous refraction-type profiles with closely spaced single-seismometer groups. Particularly, if the data is magnetically recorded through constant gain amplifiers, these studies provide the

information necessary for estimating the input noise. Using special computing equipment, the function $|F_{22}(k, f)|^2$ could be determined directly. Conventionally, however, noise waves are picked from the paper records and displayed on a time-distance plot. By making repeated playbacks through narrow filter settings, the amplitude or power of these waves, as a function of frequency, can be estimated. Figure 5 is an example of a time-distance plot with the power and frequency estimated. The power is in decibels above an arbitrary signal level. The first breaks with an apparent velocity of 5,000 and 8,000 feet per second are also shown. The fine lines represent secondary cycles of the noise arrivals. Such a plot is useful for determining the best offset distance.

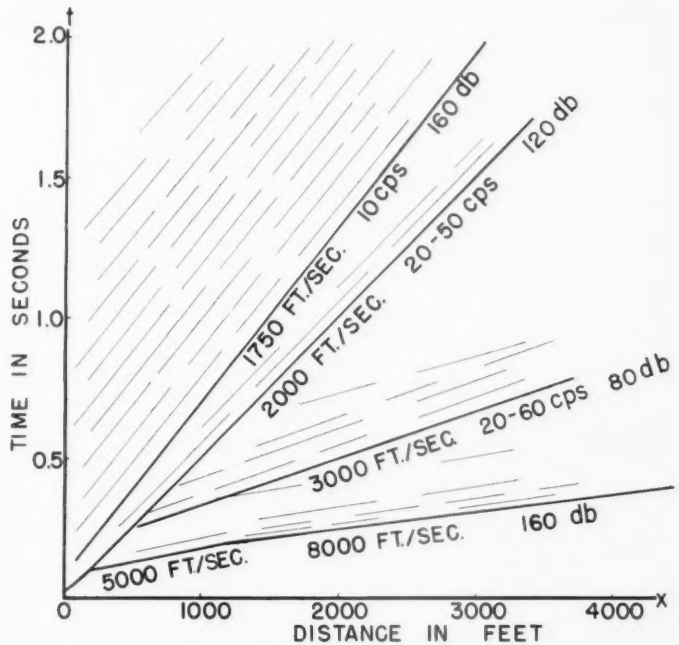

FIG. 5. Time-distance plot of noise waves.

Our estimate of the power spectrum of the noise waves $|W_{22}(k, f)|^2$ is then obtained by drawing segments of the lines $k=f/c$ on the k-f plane where c is the apparent velocity of the waves. The segment of the line displayed is determined by the estimated frequency content from the time-distance plot. Figure 6 shows the power spectrum representation of the noise waves in Figure 5. In addition, distortion components of the low frequency high amplitude wave are also shown.

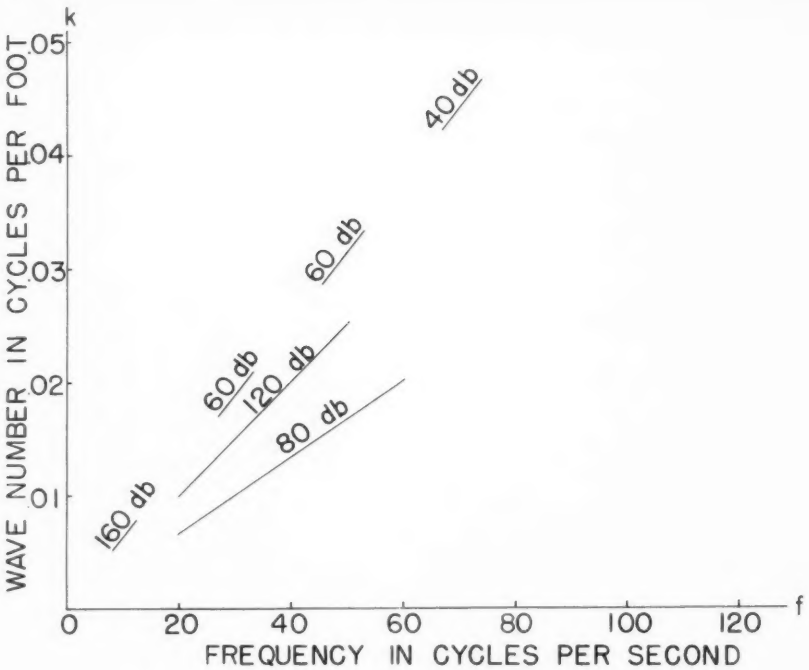

FIG. 6. Double power spectrum representation of noise plane waves.

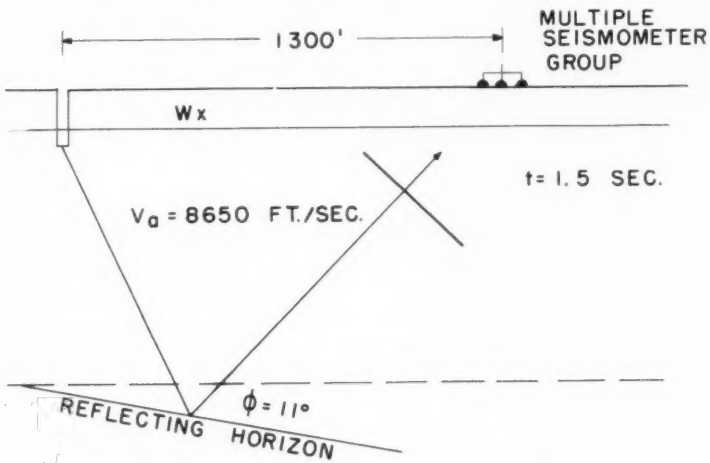

FIG. 7. Geometry for estimating apparent velocity of reflections.

For example, the 40 db line represents one-tenth of one percent seventh harmonic distortion.

Estimation of the random noise from paper records is somewhat more difficult. However, if we make the assumption of equation (29) we can estimate α by observing the rate at which the non-wave noise appears to become incoherent with increasing group spacing ξ. If coherency at a five-foot spacing is about one-third what it was at zero spacing, we can estimate α as .032. This is the value used in the function shown in Figure 4.

Estimation of the Signal

As our first estimate of the signal, we determine the minimum apparent velocity of the expected reflections. This estimate is based on offset distance, reflection time, average velocity, and dip. Figure 7 shows an example giving an apparent velocity of 30,000 feet per second. Assuming that the frequency content of this reflection lies between 30 and 75 cps, its power spectrum will be as shown in Figure 8, superimposed on the wave noise and random noise. The power spectrum of a reflection with a greater apparent velocity is also shown. Thus, in the

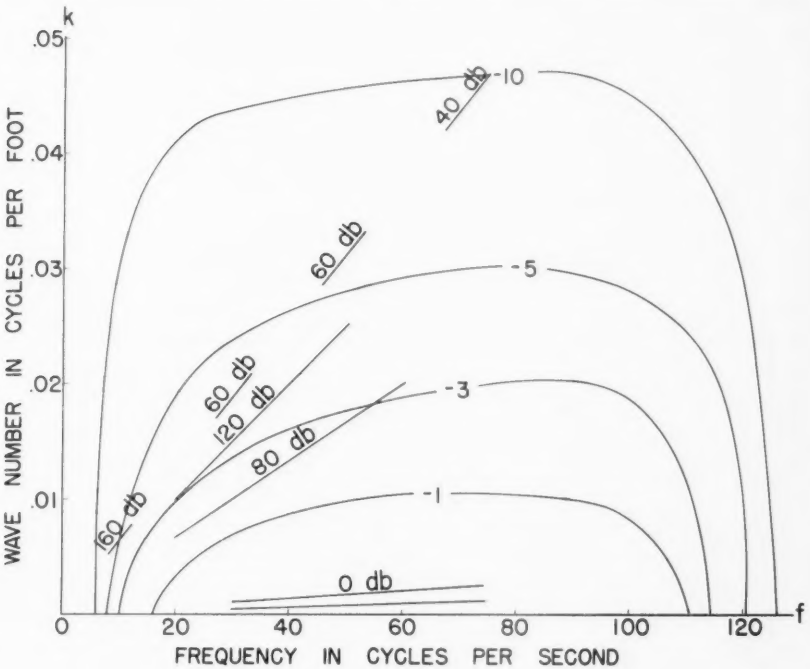

FIG. 8. Double power spectrum representation of noise and signal.

vicinity of a given x, we assume that the reflection is a plane wave $S_{11}(t-(x/c))$.

The second approximation to the signal is obtained by considering the effects of weathering and elevation variations. Here we write the signal as

$$S_{11}\left[t - \frac{x}{c} - T_w(x) - T_e(x)\right]$$

where $T_w(x)$ is the weathering correction as a function of x and $T_e(x)$ is the elevation correction as a function of x. The power spectrum of the signal will then be

$$\begin{aligned} |S_{22}(k,f)|^2 = \int\int_{-\infty}^{\infty}\int\int S_{11}\left[t - \frac{x}{c} - T_w(x) - T_e(x)\right] \\ \cdot S_{11}\left[t + \tau - \frac{x}{c} - \frac{\xi}{c} - T_w(x+\xi) - T_e(x+\xi)\right] e^{-j2\pi(f\tau - k\xi)} dx\,dt\,d\xi\,d\tau. \end{aligned} \tag{35}$$

If we let

$$\alpha = t - \frac{x}{c} - T_w(x) - T_e(x), \tag{36}$$

$$\beta = \tau - \frac{\xi}{c} + T_w(x) - T_w(x+\xi) + T_e(x) - T_e(x+\xi), \tag{37}$$

and

$$\rho(x,\xi) = T_w(x) - T_w(x+\xi) + T_e(x) - T_e(x+\xi), \tag{38}$$

and substitute into equation (35), we get

$$\begin{aligned} |S_{22}(k,f)|^2 = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} S_{11}(\alpha)S_{11}(\alpha+\beta)e^{-j2\pi f\beta}d\alpha d\beta \\ \cdot \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{-j2\pi\xi((f/c)-k)}e^{-j2\pi f\rho(x,\xi)}dx\,d\xi, \end{aligned} \tag{39}$$

or

$$|S_{22}(k,f)|^2 = |S_{22}(f)|^2 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{-j2\pi\xi((f/c)-k)}e^{-j2\pi f\rho(x,\xi)}dx\,d\xi. \tag{40}$$

Using equations (38) and (40) various cases may be worked out for weathering and elevation variations as a function of x. A particular case of interest is that in which $\rho(x,\xi)$ is small. Here we can expand the right hand exponential and, neglecting higher order terms, write equation (40) as

$$|S_{22}(k,f)|^2 \simeq |S_{22}(f)|^2 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{-j2\pi\xi((f/c)-k)}\left[1 - j2\pi f\rho - \frac{(2\pi f\rho)^2}{2}\right] dx\,d\xi. \tag{41}$$

Integrating with respect to x, and assuming that the weathering and elevation variations are independent, we obtain

$$|S_{22}(k,f)|^2 \simeq |S_{22}(f)|^2 \int_{-\infty}^{\infty} e^{-i2\pi\xi((f/c)-k)} \cdot \left\{1 - \frac{(2\pi f)^2}{2}[2\phi_{ww}(0) + 2\phi_{ee}(0) - 2\phi_{ww}(\xi) - 2\phi_{ee}(\xi)]\right\} d\xi, \quad (42)$$

where

$$\phi_{ww}(\xi) = \int_{-\infty}^{\infty} T_w(x) T_w(x+\xi) dx, \quad (43)$$

$$\phi_{ee}(\xi) = \int_{-\infty}^{\infty} T_e(x) T_e(x+\xi) dx, \quad (44)$$

and

$$\int_{-\infty}^{\infty} \rho(x,\xi) dx = 0. \quad (45)$$

Integration with respect to ξ then gives

$$\begin{aligned} |S_{22}(k,f)|^2 \simeq{}& |S_{22}(f)|^2 \delta\left(\frac{f}{c} - k\right) \\ &- (2\pi f)^2 |S_{22}(f)|^2 [\phi_{ww}(0) + \phi_{ee}(0)] \delta\left(\frac{f}{c} - k\right) \\ &+ (2\pi f)^2 |S_{22}(f)|^2 \left[\Phi_{ww}\left(\frac{f}{c} - k\right) + \Phi_{ee}\left(\frac{f}{c} - k\right)\right]. \end{aligned} \quad (46)$$

The first term on the right hand side of equation (46) represents the plane wave that would exist in the absence of weathering and elevation variations. The second term represents a correction to the frequency content of this plane wave due to the weathering and elevation variations. It is seen that the higher frequencies are more sensitive to this correction, and that the magnitude of the correction is proportional to the sum of the variances $\phi_{ww}(0)$ and $\phi_{ee}(0)$ of the weathering and elevation corrections. The third term represents a broadening of the line $(f/c) = k$, since the power spectra of the weathering and elevation variations $\Phi_{ww}((f/c) - k)$ and $\Phi_{ee}((f/c) - k)$ can be non zero when $f/c \neq k$. Thus weathering and elevation variations have two effects on the signal line in Figure 8.

In the above discussion we have defined the variance as the integral over all x. In practice, however, we are only interested in a finite interval along x, and, in general, the variance will decrease as the interval decreases. Also, since we make weathering and elevation time corrections to the records, we are in effect

subtracting out a variable mean from the variations. This will also tend to reduce $\phi_{ww}(0)$ and $\phi_{ee}(0)$.

CRITERIA FOR BEST SYSTEM POWER RESPONSE

The general definition, which we will use, of the best system power response will be that response which maximizes the signal-to-noise ratio, subject to the condition that the signal be passed relatively undistorted. For this purpose, phase must also be considered. If functional representations of the signal and noise are known, the definition of best response may be formalized, and optimum solutions computed. However, in this paper we will treat the optimization process in a qualitative manner.

From Figure 8, it is seen that the signal is confined to the region between $f=30$ cps, $f=75$ cps, $k=0$ cpft and $k=.0025$ cpft. The noise, however, covers the entire k-f plane. Ideally, therefore, we would like to pass intact the region containing the signal, and totally reject the rest of the k-f plane. In practice, of course, total rejection is not possible. However, with this objective in mind, we can proceed to make a judicious choice of multiple seismometer array and filter setting such that we reject the maximum amount of noise, but do not distort the signal.

Before discussing the design of seismometer arrays, let us investigate two other factors which will be significant in determining the effectiveness of multiple seismometers. We know from experience that multiple seismometer arrays in practice will be subject to two types of fluctuations. First, there will be a certain variability of plant and seismometer response within a group. Secondly, there will be a certain variability in the location of the individual seismometers. Thus, referring to equation (6), if the theoretical weighting factors in a group are $H_1^*(i)$, the actual weighting factors will be $H_1^*(i)(1+a_i)$ where the a_i's represent the fluctuations in plant and response. Similarly, if the theoretical locations of the seismometers within a group are ξ_i, the actual locations will be $\xi_i+\epsilon_i$ where the ϵ_i's represent the fluctuations in location. Therefore, the actual complex wave number response of the group of multiple seismometers will be

$$H_2^0(k) = \sum_{i=1}^{n} H_1^*(i)[1 + a_i]e^{-i2\pi k(\xi_i+\epsilon_i)}. \tag{47}$$

The actual power wave number response will then be

$$|H_2^0(k)|^2 = \sum_{i=1}^{n} H_1^*(i)[1 + a_i]e^{-i2\pi k(\xi_i+\epsilon_i)} \sum_{l=1}^{n} H_1^*(l)[1 + a_l]e^{i2\pi k(\xi_l+\epsilon_l)}. \tag{48}$$

Again we assume that $2\pi k(\epsilon_i-\epsilon_l)$ is small compared with 1, so that we can expand the exponential

$$e^{-i2\pi k(\epsilon_i-\epsilon_l)} \simeq \left[1 - i2\pi k(\epsilon_i - \epsilon_l) - \frac{(2\pi k)^2}{2}(\epsilon_i - \epsilon_l)^2\right].$$

Thus we can write equation (48) as

$$|H_2^0(k)|^2 \simeq \sum_{i=1}^{n}\sum_{l=1}^{n} H_1^*(i)H_1^*(l)e^{-j2\pi k(\xi_i-\xi_l)}[1 + a_i + a_l + a_ia_l] \cdot\left[1 - j2\pi k(\epsilon_i - \epsilon_l) - \frac{(2\pi k)^2}{2}(\epsilon_i - \epsilon_l)^2\right]. \tag{49}$$

If the a's and ϵ's are independent random variables with zero mean, and the theoretical power wave number response is denoted by $|H_2^*(k)|^2$ as in equation (6), then the expected value of $|H_2^0(k)|^2$ will be approximately given by

$$\langle |H_2^0(k)|^2\rangle \simeq |H_2^*(k)|^2 + \sigma_a^2|H_2^*(0)|^2 + (2\pi k)^2\sigma_\epsilon^2[|H_2^*(0)|^2 - |H_2^*(k)|^2], \tag{50}$$

where σ_a^2 and σ_ϵ^2 are the respective variances of the a's and the ϵ's. Now in general we will be interested in the responses for which $|H_2^*(0)|^2 \geqq |H_2^*(k)|^2$. In such cases all the terms in equation (50) will be positive. Thus, the actual power wave number response will be the sum of the theoretical power wave number response, a constant term, and a term containing k. Therefore, if σ_a^2 and σ_ϵ^2 are significant, a critical choice of $|H_2^*(k)|^2$ will not necessarily give a critical $\langle |H_2^0(k)|^2\rangle$ and in particular $\langle |H_2^0(k)|^2\rangle$ will not possess zeros or points of complete rejection.

Design of Seismometer Arrays

When σ_a^2 and σ_ϵ^2 are significant, the design of optimum seismometer arrays should be based on equation (50). However, for simplicity we will consider a method based on the theoretical response only. Referring to the discussion of Figure 8 above, and accepting the fact that we cannot completely reject individual noise waves, we can choose as our ideal complex wave number response a function which uniformly passes the signal with zero phase shift and uniformly rejects the noise. Such a function is shown in Figure 9. Further, if the intervals

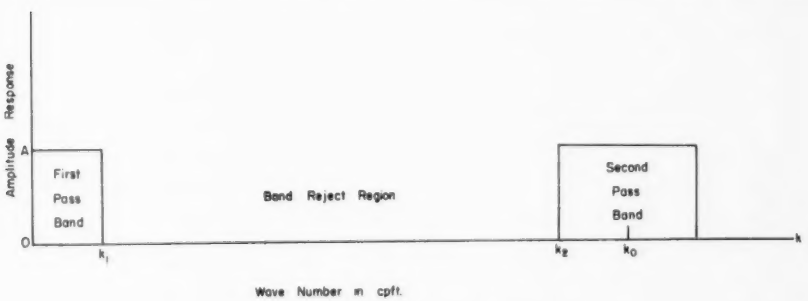

FIG. 9. Ideal multiple seismometer response.

between seismometers in the array are multiples of some fundamental interval, the theoretical response will be periodic. For this reason we have selected a periodic ideal response. The cutoff point of the first band pass occurs at $k=k_1$, the appropriate point to pass the signal. The low cut point of the second band pass occurs at $k=k_2$, a value greater than that of the noise waves. The center of the second band pass lies at $k=k_0$. Clearly, we could have chosen the center of the second band pass to lie at any value of k greater than k_0. However, a certain efficiency results from selecting this value as small as possible.

The ideal complex wave number response may be approximated in a variety of ways. However, the following discussion will be limited to approximations using evenly spaced seismometers in linear arrays. If we use the "least squares" criterion as our measure of goodness of fit, we know from the theory of Fourier series that the best fit for n seismometers will be achieved when the weighting factors of the seismometers are

$$H_1^*(i) = A\int_{-k}^{k_1} e^{-i2\pi(i-(n+1)/2)\,k/k_0}dk = \frac{A}{\pi}\,\frac{\sin\left[2\pi\left(i-\dfrac{n+1}{2}\right)\dfrac{k_1}{k_0}\right]}{\left(i-\dfrac{n+1}{2}\right)\dfrac{1}{k_0}}, \quad (51)$$

where $1/k_0$ is the spacing between seismometers. In particular, it should be noted that as the first band pass is decreased in width, $k_1\to 0$, or as the ratio $(k_1/k_0)\to 0$, $H_1^*(i)$ approaches a constant for all values of i. Now the behavior of the approximate wave number response in the vicinity of the first band pass cutoff can be of significance. But we know from the Gibbs phenomenon that the Fourier series does not converge uniformly in the vicinity of this discontinuity. Therefore, a better choice of seismometer weighting coefficients might be those from the Fejér polynomial approximation to the ideal response,

$$H_1^*(i) = \left[\frac{n-\left|i-\dfrac{n+1}{2}\right|}{n}\right]\frac{A}{\pi}\,\frac{\sin\left[2\pi\left(i-\dfrac{n+1}{2}\right)\dfrac{k_1}{k_0}\right]}{\left(i-\dfrac{n+1}{2}\right)\dfrac{1}{k_0}}. \quad (52)$$

Clearly the use of weighting factors to approximate the ideal response leads to some operational difficulties. From equations (51) and (52) it is seen these weighting factors must be changed each time the ratio k_1/k_0 changes. One solution would be to use the minimum value of k_1/k_0 that might be anticipated. However, as we have already seen, the weighting factors from equation (51) approach a constant for small k_1/k_0, and multiple seimometer strings constructed on the principle of equation (52) would still be limited in their flexibility.

An alternative to the weighting factor method is that of locating seismometers with equal outputs according to a linear density of

$$\frac{\sin 2\pi x k_1}{x} \quad \text{or} \quad \frac{n - k_0 x}{n} \frac{\sin 2\pi x k_1}{x}.$$

Similarly, pattern arrays with these same cross-sectional densities may be used. Finally, the combination of multiple seismometers and multiple holes may be so chosen that the combined response approximates the ideal complex wave number response.

Another possibly more practical approach to the design of multiple seismometer arrays consists of initially restricting the array to a line of evenly spaced seismometers with equal weighting factors. Here the power wave number response is given by

$$| H_2^*(k) |^2 = \left[\frac{\sin\left(\pi n \frac{k}{k_0}\right)}{\sin\left(\frac{\pi k}{k_0}\right)} \right]^2, \tag{53}$$

where n is the number of seismometers and $1/k_0$ is the spacing between seismometers. This is the function used in the example shown in Figure 1. Clearly this function possesses pass bands at multiples of k_0 just as did the ideal response. However, the shapes of the pass bands are sufficiently different from those of the ideal response that a new definition of the cutoff point is required. For this purpose we use the conventional definition of the cutoff as being that point which has half the maximum power response. However, since our signal waves will in general not have significant values at $k=0$, the effective maximum power response will occur at some value, k_3, of k greater than zero. Thus, if k_1 denotes the cutoff wave number on the first pass band,

$$\left[\frac{\sin\left(\frac{\pi n k_1}{k_0}\right)}{\sin\left(\frac{\pi k_1}{k_0}\right)} \right]^2 = .5 \left[\frac{\sin\left(\frac{\pi n k_3}{k_0}\right)}{\sin\left(\frac{\pi k_3}{k_0}\right)} \right]^2, \tag{54}$$

or for large n,

$$\frac{\sin\left(\frac{\pi n k_1}{k_0}\right)}{\sin\left(\frac{\pi n k_3}{k_0}\right)} = .707 \frac{k_1}{k_3}. \tag{55}$$

Thus if $k_1 \simeq 3k_3$,

$$3 - 4 \sin^2\left(\frac{\pi n k_1}{3k_0}\right) \simeq .707 \times 3. \tag{56}$$

or

$$k_1 \simeq .463 \frac{k_0}{n} \cdot \tag{57}$$

If $k_1 \simeq 2k_3$, then

$$k_1 \simeq \frac{k_0}{2n} \cdot \tag{58}$$

Equation (58) will be the equation we shall use for our definition of the cutoff point. The power response at this point then corresponds to 40 percent of the response at $k = 0$, or approximately 8 db down.

From equation (58) we see that the choice of the cutoff point specifies the product of the number of seismometers n and the spacing between seismometers $h = 1/k_0$, or effectively, the length of the seismometer array. Also, we have seen that the location of the second band pass, at $k = k_0$, is determined by the spacing between seismometers $h = 1/k_0$. Thus, from Figure 8, we can specify both nh and the maximum spacing $h_{\max}$ or the minimum number of seismometers $n_{\min}$. Next we must determine the number of seismometers required to give us the desired signal-to-noise ratio improvement.

The average power response of equation (53) is given by

$$\frac{1}{k_0} \int_{-k_0/2}^{k_0/2} \left[\frac{\sin\left(\frac{\pi n k}{k_0}\right)}{\sin\left(\frac{\pi k}{k_0}\right)} \right]^2 dk = n. \tag{59}$$

The average power response in the band pass as defined by equation (58) is, for large n, approximately

$$\frac{2n}{k_0} \int_0^{k_0/2n} \left[\frac{\sin\left(\frac{\pi n k}{k_0}\right)}{\frac{\pi k}{k_0}} \right]^2 dk = .8n^2. \tag{60}$$

The average power response in the band reject region, for large n, is approximately

$$\frac{nk_0 - .8nk_0}{k_0 - \frac{k_0}{n}} = \frac{.2n}{1 - \frac{1}{n}} \simeq .2n. \tag{61}$$

Thus, if the signal is confined to the band pass region, and the noise is confined to the band reject region, the average improvement in the signal-to-noise power ratio will be

$$R^2 = \frac{.8n^2}{.2n} = 4n, \tag{62}$$

or in amplitude signal-to-noise ratio

$$R = 2\sqrt{n}. \tag{63}$$

If the signal is confined to the band pass region, and the noise extends over all k, the average improvement in signal-to-noise power ratio will be

$$R^2 = \frac{.8n^2}{n} = .8n. \tag{64}$$

If the signal is confined to $k=0$, and the noise extends over all k, the average improvement in signal-to-noise power ratio will be

$$R^2 = \frac{n^2}{n} = n. \tag{65}$$

This last relation and the preceding assumptions are used in the conventional discussion of random noise.

Multiple Seismometer Nomogram

Figure 10 is a nomogram for determining nh (number of seismometers times seismometer spacing) and $h_{\max}$ (maximum allowable seismometer spacing) according to the criteria previously discussed. The maximum signal wave number k_1 is estimated from the anticipated dip ϕ, the average velocity V_a, the record time t, the offset distance x, and the highest significant frequency component f_H. The lowest noise velocity V_L, and f_H determine $h_{\max}$. The equation used for nh is

$$nh = \frac{V_a}{2f_H} \frac{(V_a t/x)}{\left\{1 + \sin\phi\left[\sqrt{\left(\frac{V_a t}{x}\right)^2 - \cos^2\phi} - \sin\phi\right]\right\}}, \tag{66}$$

and the equation for $h_{\max}$ is

$$h_{\max} = \frac{V_L}{f_H}. \tag{67}$$

The use of logarithmic ordinates and abscissas, and 45° lines, permits the necessary multiplications and divisions. The curves provide the trigonometric computations. The numbers on the left hand vertical scale also apply to the V_a scale. The n scale is in number of seismometers, the V_a scale is in 1,000 feet per second, the V_L scale is in 100 feet per second, and the f_H scale is in cps. The numbers on the f_H scale also apply to the V_L scale. The numbers on the bottom horizontal scale also apply to the center horizontal scale where h and $h_{\max}$ are in feet. The

nh scale is in feet and the V_at/x scale is dimensionless. The ϕ curves are in degrees of dip where the curves concave downwards represent positive dip, and those concave upwards represent negative dip.

The following example illustrates the application of this nomogram. First we wish to determine nh from the values of $x=1{,}300$ feet, $t=1.5$ sec., $V_a=8{,}650$ feet per second, $\phi=11°$, and $f_H=75$ cps. The intersection of the horizontal line V_a

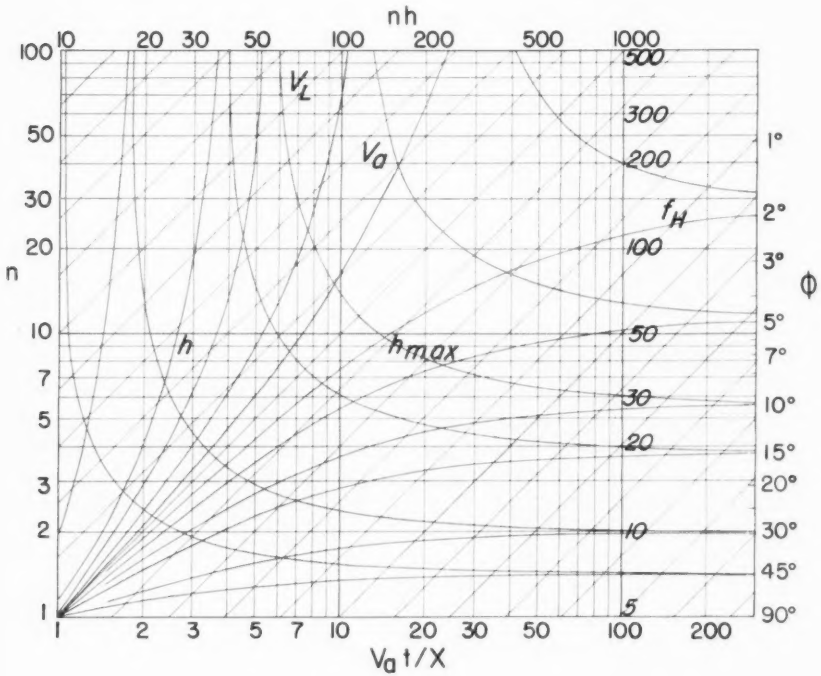

FIG. 10. Multiple seismometer nomogram.

$=8{,}650$ feet per second and the slant line $f_H=75$ cps determines a vertical line. The intersection of this vertical line with the center horizontal axis determines another slant line which we shall use after an additional operation. The intersection of the vertical line V_at/x with the interpolated curve $\phi=11°$ determines a horizontal line. The intersection of this horizontal line with the slant line previously determined, gives us the vertical line $nh=200$ feet. Next we wish to determine h_{max} from the values $V_L=1{,}750$ feet per second and $f_H=75$ cps. The intersection of the horizontal line $V_L=1{,}750$ feet per second and the slant line $f_H=75$ cps gives us the vertical line $h_{max}=23.4$ feet.

Choice of Filter Settings

Again referring to Figure 8 ,we see that in addition to selecting the best multiple seismometer response, we wish to apply some selective filtering in order to maximize the signal-to-noise ratio. Here also, we require that the filter pass the signal undistorted with the exception of an unavoidable constant time shift. Thus, in order to remove as much random noise as possible as well as wave noise, we choose the cutoff points on our filter at f_L, the lowest significant signal frequency, and f_H, the highest significant signal frequency. Within the band pass we require that the phase shift be approximately linear with an $f=0$ intercept of even multiples of $\pm\pi$. Odd multiples of $\pm\pi$ give a phase reversal in addition to a time shift.

A factor not as obvious as those above is the shape of the band pass itself. Referring to Figures 3 and 8, we see that in order to minimize distortion of the signal we would like the contours of the system power response to be parallel to the signal lines in the first band pass. This result has been partially achieved in Figure 3, by choosing the filter response curve shown in Figure 2.

CONCLUSIONS

In the preceding sections we have presented some general theory and techniques for analyzing, estimating, and displaying the characteristics of wave noise, random noise, and signal. We have also discussed the modifications resulting from weathering and elevation variations. In addition, we have selected some criteria for best system power response, and attempted to show how the wave number-frequency plot of the input data may be used in the design of multiple seismometer arrays, and the choice of filter settings. The examples cited were not intended to be all inclusive, but were presented merely to illustrate the applications of this analysis.

APPENDIX

Double Spectrum of Damped Plane Wave

Let

$$N_{11}(x, t) = D_{11}(x)P_{11}\left(t - \frac{x}{c}\right).$$

Then

$$\phi_{NN}(\xi, \tau) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} D_{11}(x)D_{11}(x+\xi)P_{11}\left(t - \frac{x}{c}\right)P_{11}\left(t + \tau - \frac{x}{c} - \frac{\xi}{c}\right)dxdt.$$

Making the substitution $t=\alpha+(x/c)$, and collecting products, we obtain

$$\begin{aligned}\phi_{NN}(\xi, \tau) &= \int_{-\infty}^{\infty} D_{11}(x)D_{11}(x+\xi)dx \int_{-\infty}^{\infty} P_{11}(\alpha)P_{11}\left(\alpha + \tau - \frac{\xi}{c}\right)d\alpha \\ &= \phi_{DD}(\xi)\phi_{PP}\left(\tau - \frac{\xi}{c}\right)\end{aligned}$$

where $\phi_{DD}(\xi)$ and $\phi_{PP}[\tau-(\xi/c)]$ are the single variable autocorrelation functions of $D_{11}(x)$ and $P_{11}(\alpha)$ respectively. The power spectrum is then given by

$$| N_{22}(k, f) |^2 = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \phi_{DD}(\xi)\phi_{PP}\left(\tau - \frac{\xi}{c}\right) e^{-j2\pi(f\tau - k\xi)} d\xi d\tau.$$

Making the substitution $\tau=\beta+(\xi/c)$, we obtain

$$| N_{22}(k, f) |^2 = \int_{-\infty}^{\infty} \phi_{DD}(\xi) e^{-j2\pi((f/c)-k)\xi} d\xi \int_{-\infty}^{\infty} \phi_{PP}(\beta) e^{-j2\pi f\beta} d\beta$$

$$= \left| D_{22}\left(\frac{f}{c} - k\right)\right|^2 | P_{22}(f) |^2,$$

where $|D_{22}|^2$ and $|P_{22}|^2$ are the power spectra in one variable of D_{11} and P_{11} respectively.

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GEOPHYSICS, VOL. XXI, NO. 2 (APRIL, 1956), PP. 361–367, 1 FIG.

A COMPARISON OF ADDITIVE AND MULTIPLICATIVE COMPOUNDING*

KARL DYK†

ABSTRACT

Additive and multiplicative compounding of seismometer outputs are compared. In the equations developed for multiplicative compounding some terms involve products of signal and noise, and an arbitrary division of these terms between signal and noise is made to facilitate handling. Under the assumptions made it is developed that for low signal-to-noise ratios (less than 0.8) additive compounding provides a greater improvement in signal-to-noise ratio than does multiplicative compounding unless large numbers of units are compounded.

INTRODUCTION

The gain in signal-to-noise ratio to be expected from the additive compounding of multiple seismometers was investigated by Klipsch (1936). He found the "average expectancy of this gain" to be proportional to the square root of the number of seismometers for random noises. The purpose of this investigation is to determine the effect of multiplicative compounding of the outputs of the several seismometers and to compare this with the results of additive compounding. It will be assumed that signal and noise are independent and that the noise is composed of components having random phase relationships. The effects of compounding on character will not be discussed.

The analysis is concerned with seismometer spacings for which discreet waves generally can not be followed from one seismometer to adjacent seismometers. Such spacing may be comparatively short in many areas in which multiple geophones are used and not practically realizable in other areas, for example, when ground roll is a serious factor.

RELATIONS AT ONE SEISMOMETER

Let the signal output of a seismometer be

$$S = S_0 \sin \theta.$$

Let the noise be isofrequency (this assumption is reasonable for the case of peaked filters in common use) with m_1 components having random phase relationships and equal amplitudes a_1; m_2 components with random phase relationships and equal amplitudes a_2; m_3 similar components with amplitudes a_3; etc. The resultant average noise amplitude (expectation) is then, after Rayleigh (1877, v. 1, p. 41):

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$$E(r_1) = \frac{2}{\sum_1^k m_i a_i^2} \int_0^\infty e^{-r^2/\sum_i^k m_i a_i^2 r^2} dr$$

$$= \frac{\pi^{1/2}}{2} \left(\sum_1^k m_i a_i^2 \right)^{1/2}$$

$$= \frac{1}{2} \pi^{1/2} Q^{1/2},$$

where

$$Q = \sum_1^k m_i a_i^2.$$

The average signal amplitude (expectation) is

$$E(S_1) = \frac{1}{\pi} \int_0^\pi S_0 \sin \theta d\theta = \frac{2}{\pi} S_0.$$

The average signal-to-noise ratio (expectation) is for one seismometer

$$E(R_1) = \frac{E(S_1)}{E(r_1)} = \frac{4 S_0}{\pi^{3/2} Q^{1/2}}.$$

ADDITIVE COMPOUNDING OF n SEISMOMETERS

Suppose there are n seismometers at each of which the noises are independent and have the characteristics described above for one seismometer, the noise amplitude expectation at each seismometer being $E(r_1)$. If the outputs at the n seismometers are added, then the noise amplitude expectation of the sum is

$$E(r_n) = \tfrac{1}{2} \pi^{1/2} n^{1/2} Q^{1/2} = n^{1/2} E(r_1).$$

If the signals are all in phase, the summed signal amplitude expectation is

$$E(S_n) = n E(S_1),$$

and the signal-to-noise ratio is

$$E(R_n) = n^{1/2} E(R_1).$$

This differs by a numerical factor from the relation developed by Klipsch (1936) since Klipsch defined the signal-to-noise ratio at one seismometer as the ratio of amplitudes and not of expectations. Klipsch apparently contemplated a single sinusoidal source of noise at each seismometer, whereas we are considering m sources with different amplitudes having random phase relationships.

SQUARING AN INDIVIDUAL SIGNAL-NOISE

The average signal amplitude before squaring is

$$E(S_1) = \frac{2}{\pi} S_0.$$

The amplitude expectation for the squared signal alone is

$$E(S^2) = \frac{1}{\pi} S_0^2 \int_0^{\pi} \sin^2\theta d\theta = \frac{1}{2} S_0^2.$$

The amplitude expectation of the squared (signal plus noise) is

$$\begin{aligned} E[(S+r)^2] &= \frac{2}{\pi Q} \int_{\theta=0}^{\theta=\pi} \int_{r=0}^{r=\infty} (S_0 \sin\theta + r)^2 e^{-r^2/Q} r dr d\theta \\ &= \frac{2S_0^2}{\pi Q} \int_{\theta=0}^{\theta=\pi} \int_{r=0}^{r=\infty} \sin^2\theta e^{-r^2/Q} r dr d\theta \\ &\quad + \frac{4S_0}{\pi Q} \int_{\theta=0}^{\theta=\pi} \int_{r=0}^{r=\infty} \sin\theta e^{-r^2/Q} r^2 dr d\theta + \frac{2}{\pi Q} \int_{\theta=0}^{\theta=\pi} \int_{r=0}^{r=\infty} e^{-r^2/Q} r^3 dr d\theta \\ &= \frac{S_0^2}{Q} \int_0^{\infty} e^{-r^2/Q} r dr + \frac{8S_0}{\pi Q} \int_0^{\infty} e^{-r^2/Q} r^2 dr + \frac{2}{Q} \int_0^{\infty} e^{-r^2/Q} r^3 dr \\ &= \frac{1}{2} S_0^2 + \frac{2}{\pi^{1/2}} S_0 Q^{1/2} + Q. \end{aligned}$$

The first term of the right-hand side is the expectation of the square of the noise-free signal while the last term is the expectation of the square of the signal-free noise. The middle term contains both signal and noise, and there is some question as to the relative content of each.

We will assume the amount of signal in the middle term to be

$$\frac{E(S^2)}{E(S^2) + E(r^2)} \times (\text{middle term}) = \frac{\frac{1}{2}S_0^2}{\frac{1}{2}S_0^2 + Q} \cdot \frac{2S_0 Q^{1/2}}{\pi^{1/2}},$$

and of the noise to be

$$\frac{Q}{\frac{1}{2}S_0^2 + Q} \cdot \frac{2S_0 Q^{1/2}}{\pi^{1/2}}.$$

The signal-to-noise ratio in the squared trace is then

$$E(R_{\square}) = \frac{S_0^2}{2Q} = \frac{\pi^3 [E(R_1)]^2}{32},$$

thus being the same as though the middle term were not present. The result is the same as would be obtained by first squaring the signal, then squaring the noise separately, and then combining the resultants. Under these conditions a gain in signal-to-noise ratio is obtained by squaring whenever

$$E(R_1) > \frac{32}{\pi^3} \simeq 1.03.$$

For $E(R_1)$ less than this value, squaring causes a deterioration of signal-to-noise ratio (over the original unsquared value).

MULTIPLYING TWO OUTPUTS

Let us now multiply two outputs for which the signals are equal and in phase; the noise of each output will be considered as independent, with the individual noise amplitude expectations of the two outputs being equal. Call the noise amplitudes r and p:

$$E[(S+r)(S+p)] = \int_0^1 \int_0^1 \int_0^1 (S+r)(S+p)\,dP_r\,dP_p\,dP_s,$$

where dP_s is the probability that S lies between S and $S+dS$, dP_r the probability r lies between r and $r+dr$, etc., and $E[(S+r)(S+p)]$ is the expectation of the product. All separate probabilities are independent:

$$E[(S+r)(S+p)]$$

$$= \frac{4}{\pi Q^2} \int_{\theta=0}^{\theta=\pi} \int_{r=0}^{r=\infty} \int_{p=0}^{p=\infty} (S_0 \sin\theta + r)(S_0 \sin\theta + p) e^{-r^2/Q} e^{-p^2/Q} r\,p\,d\theta\,dr\,dp$$

$$= \frac{S_0^2}{2} + \frac{2S_0 Q^{1/2}}{\pi^{1/2}} + \frac{\pi Q}{4}.$$

$S_0^2/2$ is the amplitude expectation of the product of the noise-free signals of the two outputs, and $\pi Q/4$ is the amplitude expectation of the product of the two random noises free from signal. Apportioning the middle term of the right-hand member as before, we obtain the signal-to-noise ratio

$$E(R_{x2}) = \frac{2S_0^2}{\pi Q} = \frac{\pi^2}{8}\,[E(R_1)]^2.$$

We note an improvement in signal-to-noise ratio over that of a single output if

$$E(R_1) > \frac{8}{\pi^2} \cong 0.81.$$

Let us compare $E(R_{x2})$ with the signal-to-noise ratio for additive compounding of two traces. We found

$$E(R_n) = n^{1/2} E(R_1),$$

whence for $n=2$

$$E(R_{x2}) = \frac{\pi^2}{16}\,[E(R_2)]^2,$$

from which $E(R_{x2}) > E(R_2)$ when

$$E(R_2) > \frac{16}{\pi^2} \cong 1.6$$

or when

$$E(R_1) > \frac{16}{2^{1/2}\pi^2} \cong 1.15.$$

MULTIPLYING n OUTPUTS

Consider now n outputs for which the signals are all in phase; the noise outputs will be considered as random with the individual noise amplitude expectations $E(r_1)$, $E(r_2)$, $\cdots$, $E(r_n)$, of all outputs being equal. Then

$$E[(S + r_1)(S + r_2) \cdots (S + r_n)]$$
$$= \int_0^1 \int_0^1 \cdots \int_0^1 (S + r_1)(S + r_2) \cdots (S + r_n) dP_s dP_{r_1} dP_{r_2} \cdots dP_{r_n},$$

where all r's and P_r's are independent. From this,

$$E[(S + r_1)(S + r_2) \cdots (S + r_n)] = \frac{{S_0}^n}{\pi^{1/2}} \frac{\Gamma\left(\frac{n+1}{2}\right)}{\Gamma\left(\frac{n}{2}+1\right)} + f(S_0Q) + \left(\frac{\pi Q}{4}\right)^{n/2},$$

$f(S_0Q)$ being the terms in which both S_0 and Q appear. Apportioning $f(S_0Q)$ between signal and noise in the same manner as before, the signal-to noise ratio $E(R_{xn})$ becomes

$$E(R_{xn}) = \frac{1}{\pi^{1/2}}\left(\frac{\pi}{2}\right)^n \frac{\Gamma\left(\frac{n+1}{2}\right)}{\Gamma\left(\frac{n}{2}+1\right)} [E(R_1)]^n$$

$$= \frac{1}{\pi^{1/2}}\left(\frac{\pi}{2}\right)^n \frac{\Gamma\left(\frac{n+1}{2}\right)}{\Gamma\left(\frac{n}{2}+1\right)} \frac{[E(R_n)]^n}{n^{n/2}}.$$

Fig. 1 shows $E(R_n)$ and $E(R_{xn})$ as functions of n. It is apparent that for a single output signal-to-noise ratio of unity, $E(R_{xn}) > E(R_n)$ for $n = 4$ or more. For a single output signal-to-noise ratio of 0.8 (about -2 *db*), $E(R_{xn}) > E(R_n)$ for $n > 10$; for $E(R_1) = 0.75$ (about -2.5 *db*) $E(R_{xn}) > E(R_n)$ for $n > 17$. For $E(R_1) = 0.5$ (not plotted) $E(R_{xn}) > E(R_n)$ for n of the order of 1,000.

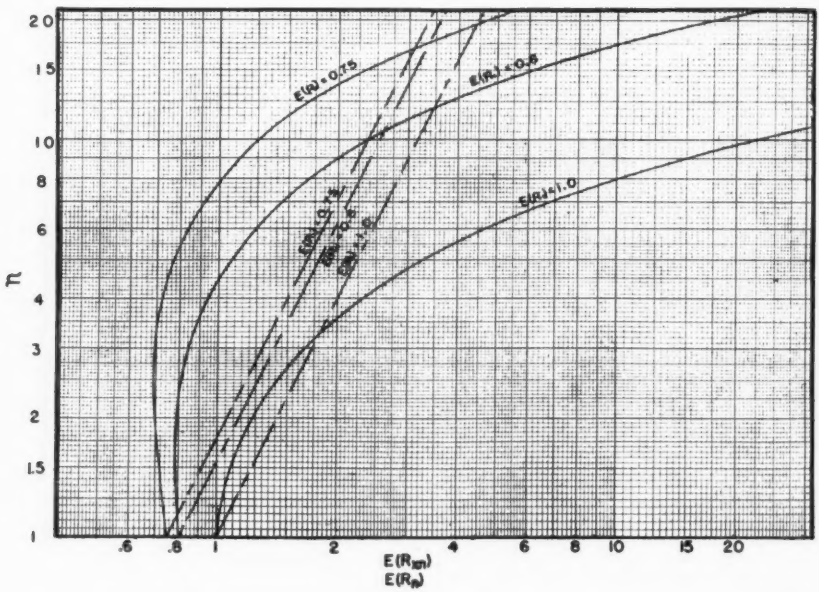

FIG. 1. Relation between the number of outputs n and the signal-to noise ratio expectation for additive compounding $E(R_n)$- - -and multiplicative compounding $E(R_{sn})$—with $E(R_1)$ as parameter.

LOW SIGNAL-TO-NOISE RATIOS

There is good evidence that signals are easily pickable with signal-to-noise ratio of unity. As a matter of fact, there are reasons to believe that the limiting tolerable ratio for picking signals amid random noise is as low as $\frac{1}{2}$ (Dyk and Eisler, 1951). The prime problem is to improve record pickability in the marginal and submarginal pickability zones, that is, for signal-to-noise ratios below, say 0.75. In these regions additive compounding improves signal-to-noise ratio more than does multiplicative compounding (under the assumptions made) until the number of compounded units become inordinately high.

HIGH SIGNAL-TO-NOISE RATIOS

The question next arises as to the value of multiplicative compounding when signal-to-noise ratios are greater than *one*, in which case an improvement over additive compounding results. In this region there is little difficulty in picking, and the tendency is to compound as little as possible with our present additive compounding in order to achieve the maximum resolving power. The relationship between cause and effect is certainly obscured much more quickly in multiplicative compounding than in additive. We therefore conclude that for visual analysis it would not be advantageous to use multiplicative compounding for high signal-

to-noise ratios. This would further appear to rule out consideration of possible combinations of multiplicative and additive compounding.

UNEQUAL NOISE EXPECTATIONS

If we have equal signal strengths in all outputs with different average noise levels in each, the results are changed somewhat in favor of multiplicative compounding over additive. However, the additional improvement is still not sufficient to appear of significant interest.

If we replace the several Q's by b_1Q, b_2Q, b_3Q, etc., the comparison of multiplicative and additive signal-to-noise ratios becomes

$$E(R_{an}) = \frac{1}{\pi^{1/2}}\left(\frac{\pi}{2}\right)^n \frac{\Gamma\left(\frac{n+1}{2}\right)}{\Gamma\left(\frac{n}{2}+1\right)} \frac{[E(R_n)]^n}{n^{n/2}} \left\{\frac{(\Sigma b)^{n/2}}{n^{n/2}(\Pi b)^{1/2}}\right\}.$$

The part outside the braces is identical with the expression when all the noise expectations are equal. For the problem at hand, the average Q may be selected so that

$$\Sigma b = n,$$

leaving us with

$$\frac{1}{(\Pi b)^{1/2}}$$

as the factor in braces, which measures the departure between the equal and unequal noise-intensity cases. While it is fairly easy to outline conditions under which the factor becomes appreciable, such conditions are not considered common. If the noise expectations vary through a range of 2 to 1, n needs to be fairly large before the factor becomes sufficiently important seriously to affect the discussion under "Low Signal-to-Noise Ratios." The subject of unequal noise expectations has not been exhausted.

OTHER MODES OF COMPOUNDING

Since the improvements in signal-to-noise ratio to be expected from additive compounding appear to be different from those to be expected for multiplicative compounding, it seems possible that other modes of compounding may exist which are particularly advantageous for the lower signal-to-noise ratios.

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GEOPHYSICS, VOL. XXI, NO. 2 (APRIL, 1956), PP. 368-387, 17 FIGS.

STRUCTURAL AND SEISMIC DEFORMATIONS ALONG NORMAL FAULTS IN THE EASTERN VENEZUELAN BASIN*

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ABSTRACT

Seismic reflections in normal fault zones in the Eastern Venezuelan basin usually appear distorted. Studies of reflections over fault structures delineated by drilling indicate that this is due to the similar effects of two entirely different phenomena:

1. True structural deformation of beds on the downthrown side.
2. Purely seismic distortion of reflections from underneath the fault.

Analysis indicates that the structural deformations form an integral part of the fault zone; the purely seismic distortion is caused by passage of the wave through this zone of deformation.

INTRODUCTION

In the Eastern Venezuelan basin (Figure 1) a large number of normal faults have been found by seismic exploration and deep drilling. The writer has spent several years studying such faults on seismic records, sections, and maps, and comparing the seismic data with subsurface data furnished by subsequent drilling. Certain characteristic patterns recurred in all normal fault zones throughout the basin. It is the purpose of this paper to describe and analyze these patterns.

The material for the demonstration is taken from a restricted area in Central Anzoátegui (Figure 2), on the south flank of the basin, where the Company's exploration has funished the most numerous data. The geologic situation for this part of the basin is approximately this (for more detailed information, see Mencher et al., 1953, and Renz et al., in press): The sedimentary sequence is from 10,000 to 15,000 feet thick. It is mostly of Tertiary age and consists mainly of an alternation of comparatively thin sandstone and shale beds. Regional dip increases with depth, and at the same time changes direction from east (top of the section) to north (base of the section). It is northeast for the central part of the section and amounts to 3° or 4°.

The structural and seismic patterns accompanying the normal fault zones in this area may be seen in Figure 3, which represents a seismic line cutting the Araibel fault zone (the location of the line with respect to the fault zone is shown in Figures 4 and 5). On the downthrown side of the fault we observe some irregularities in the regional dip which are (proceeding from the left side of Figure 3): First, a zone of steepening of dip into the fault, or reverse drag; second, a zone of flattening or even reversal of regional dip, corresponding to normal drag at the fault; third, a second zone of steepening, and fourth, a second zone of dip reversal. These zones define two gentle troughs whose amplitude decreases upward. The troughs are about 6,000 feet wide and reach an amplitude of about 200 feet. Their axial planes are approximately vertical.

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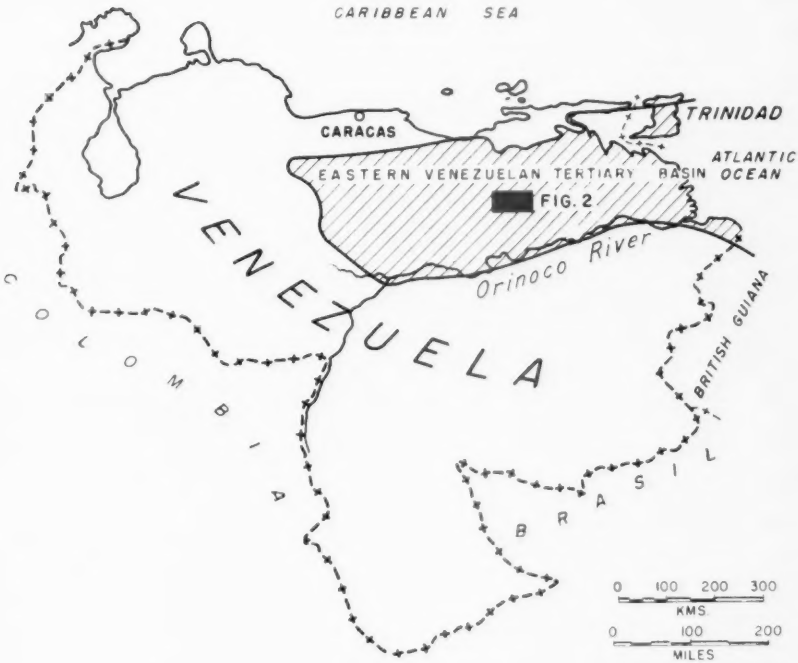


FIG. 1. *Map of Venezuela* with the location of the Eastern Venezuelan Tertiary Basin.

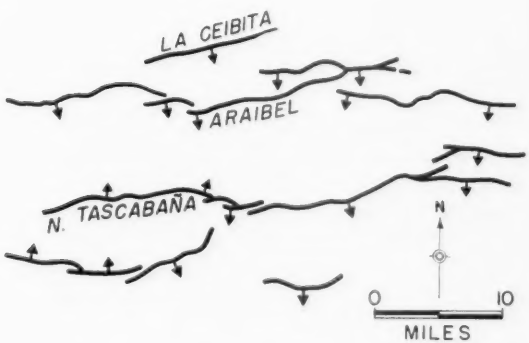


FIG. 2. *Structural map of a small area in the central part of the basin*, showing main fault trends.

Underneath the fault there are even more conspicuous irregularities. Interferences of reflections with different dips cause a confused picture on the records which is difficult to disentangle. Very few reflections from this zone can be plotted and a blank space ("shadow zone") appears on the cross-section. The segments of reflections which can be used, however, show a dip configuration similar to that above the fault. This correspondence of dip configurations above and below

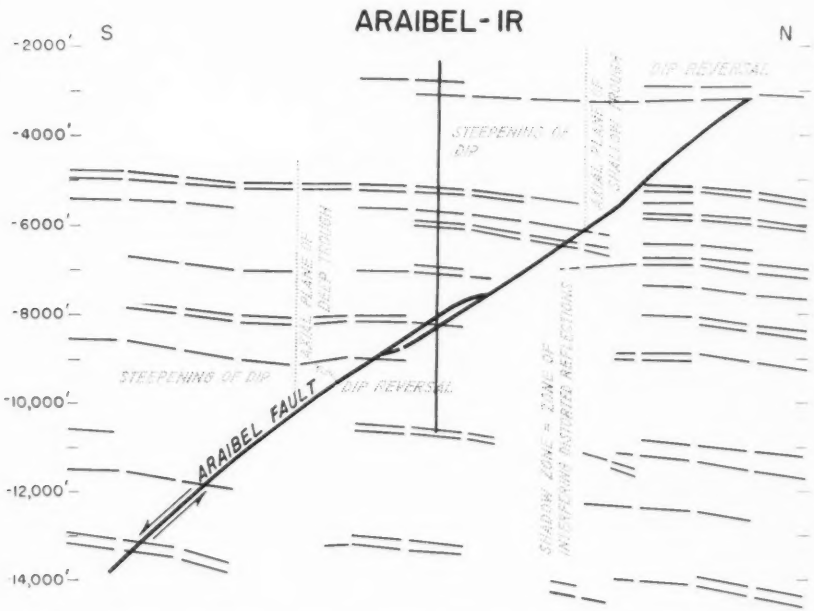


FIG. 3. *Seismic cross-section through the Araibel fault zone.* Reflections are plotted vertically, while the fault is migrated and adjusted to fit well data. *A*, *B*, *C*, *D*, are horizons correlated across the fault.

the fault is more clearly demonstrated in Figure 6 (La Ceibita Fault), where the amplitude of the troughs is very small, and interferences below the fault are moderate. These interferences appear on the records as shown in Figure 7.

A comparison of the seismic section with the well data plotted on Figures 4 and 5 shows that the steepening of dip corresponding to the south limb of the shallow trough is a true structural deformation for the section *above* the fault (Figure 4). Below the fault (Figure 5), well data show almost smooth regional dip, which is at variance with the seismic evidence. We are forced to conclude that the seismic irregularities in a fault zone consist of two parts: above the fault

there are true structural deformations; below the fault there are purely seismic distortions. These distortions invariably repeat, at least qualitatively, the true structural deformations above the fault. This is true for over 100 sections examined. It means that there must be a connection between the two phenomena. An investigation of the seismic distortion presupposes, therefore, understanding of the structural conditions of the fault zone. For that reason we shall first try

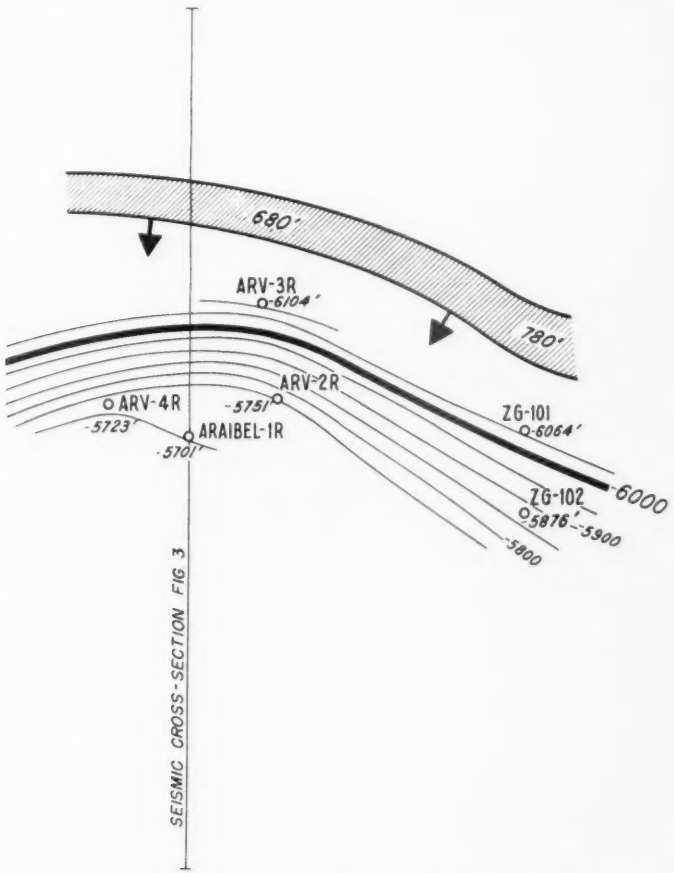
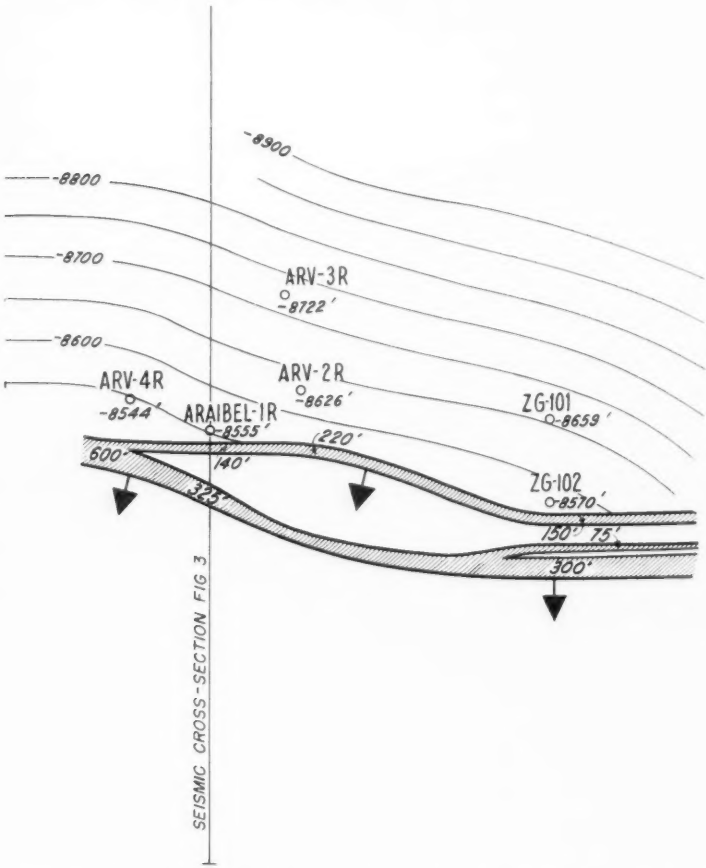


FIG. 4. *Subsea map of Araibel area on top of Oficina formation.* Dip into the fault is steeper (reverse drag) than the regional dip shown on Figure 5. There is only one fault break, and its throw is larger than the cumulative throw of the several breaks shown on Figure 5 for a deeper part of the section.

to describe and analyze the structural aspect of the fault zone in some detail; and second, we shall try to visualize what happens to a seismic wave passing through a medium structured in such a specific way.

STRUCTURAL DEFORMATIONS ON THE DOWNTHROWN SIDE (ABOVE THE FAULT)

The wells in the Araibel area give evidence for a part of the seismically observed structural deformations on the downthrown side of the faults. More com-



5. *Subsea map of Araibel area on J_1 horizon* (middle Oficina formation). Note smooth regional dip on up-side of fault, which is split up into several breaks. Numbers in fault give throw in nearest wells.

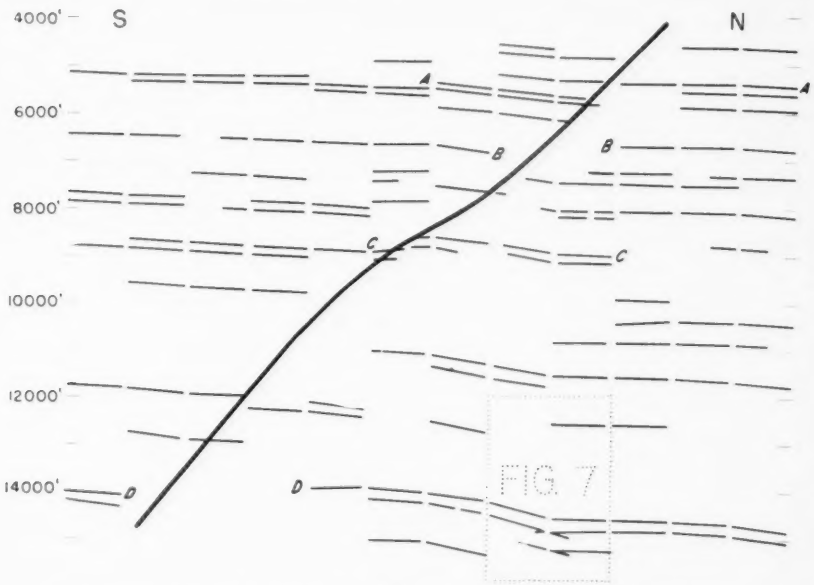


FIG. 6. *Seismic cross-section through La Ceibita fault.* The troughs on the downthrown side and the distortions beneath the fault are moderate. Reflections are plotted vertically. *A, B, C, D* are reflections correlated across the fault.

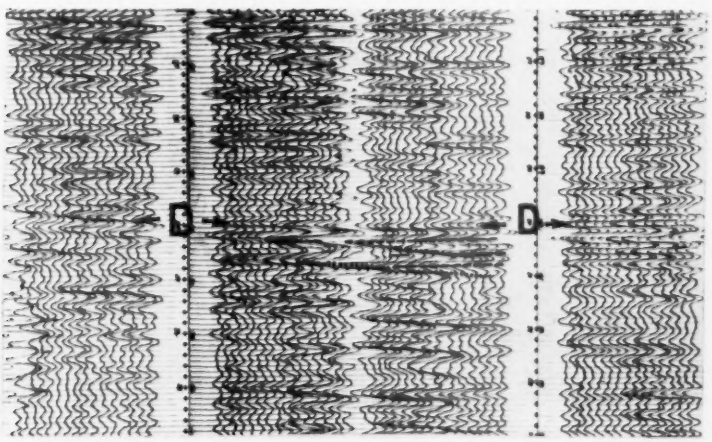


FIG. 7. *Distorted reflections from La Ceibita fault zone.* The part of the records represented corresponds to the area marked on Figure 6. Reflection *D* is the same as on the cross-section.

plete evidence is furnished by numerous wells and structure drill holes in the Boca field on the downthrown side of the North Tascabaña fault. These subsurface data (Figures 8 and 9) confirm the seismic picture and reveal essentially the structural configuration shown in Figure 3 for the Araibel fault: two gentle troughs, one on the deep horizons (Figures 8 and 9) and one on the shallow horizons (Figure 9); width and amplitude of the troughs are similar in both cases, and the amplitude decreases upward.

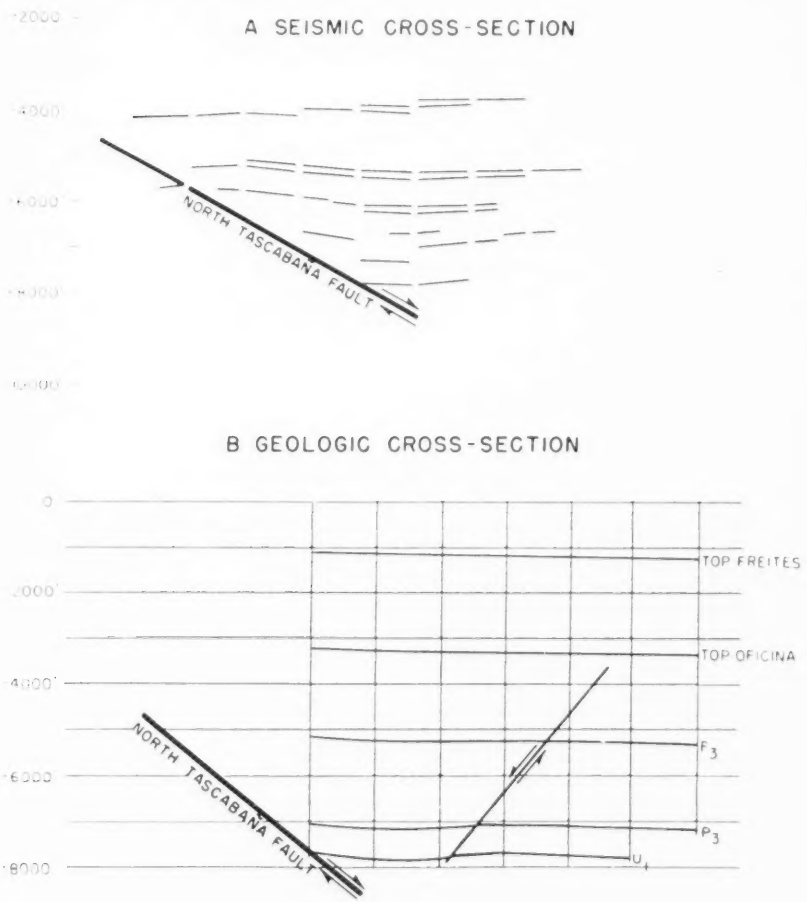


FIG. 8. *Seismic and geologic cross sections through the Boca structure* on the downthrown side of the North Tascabaña fault. The vertical lines on the geological section are wells. Evidence for the north limb of the shallow trough is contained in the map on the top of the Freites formation, Figure 9.

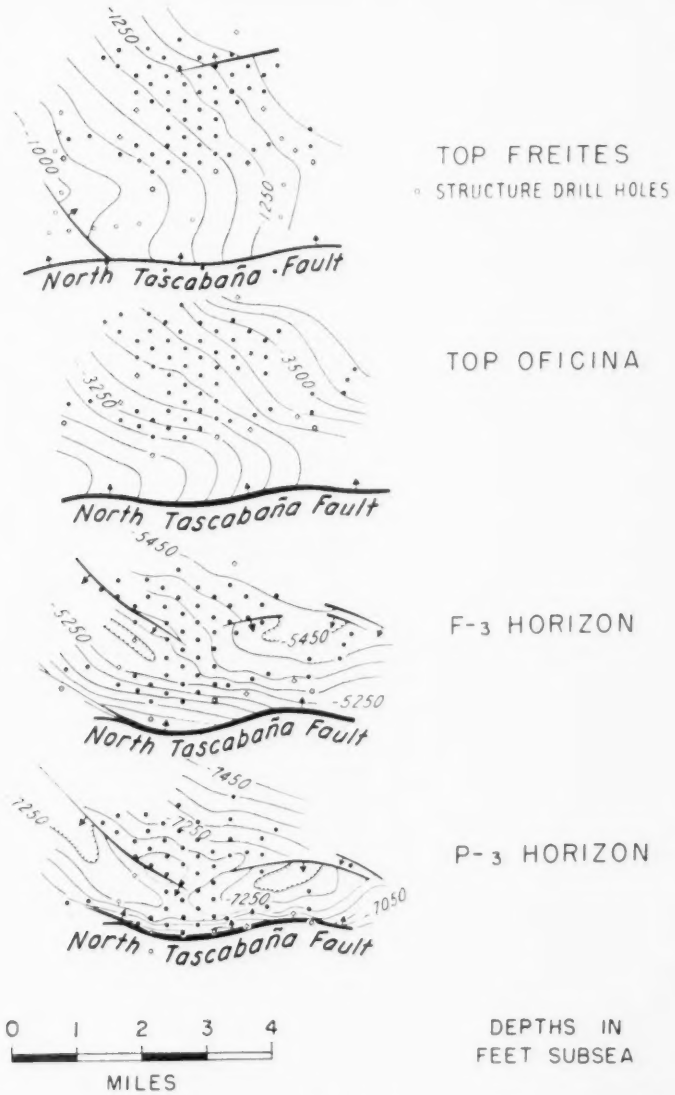


FIG. 9. *Subsurface maps of the Boca structure.* Notice the disappearance of the deep trough on the shallow horizons and the development of a shallow trough.

Normal faults in eastern Venezuela are thus complex zones of deformation up to 10,000 feet wide. The actual fault breaks are only one part of the zone. They form a complicated system which usually is the lower boundary of the zone of deformation. The individual breaks of which the system is composed (see Figures 2 and 5) are often discontinuous and curved on both maps and cross sections. They die out in the higher part of the section.

In order to obtain a more satisfactory picture of the structural conditions in these fault zones and their significance for seismic wave propagation, it is desirable to analyze, at least qualitatively, the process of their development.

Comparison with Experimental Structures

Generally speaking, these normal faults are shearing zones due to gravitational compression and horizontal extension. It is interesting to note that similar wedge-shaped complex zones of shearing deformation are well known from experiments with plastic material, for instance, from paraffin blocks strained in compression (Nádai, 1950). They originate at points of discontinuity in the medium or in its bounding surface—singularities—such as weaknesses, flaws, holes, or edges, and spread in the shearing directions as strain increases. Deformation takes place mainly along two complementary sets of surfaces of slip.

Basically similar conditions prevail in some experiments made by H. Cloos with cakes of wet clay. They were intended to simulate actual geological processes, and the results resemble, in fact, observed geological features. Particularly, the experimental structure shown in Figure 10 bears a resemblance to the normal

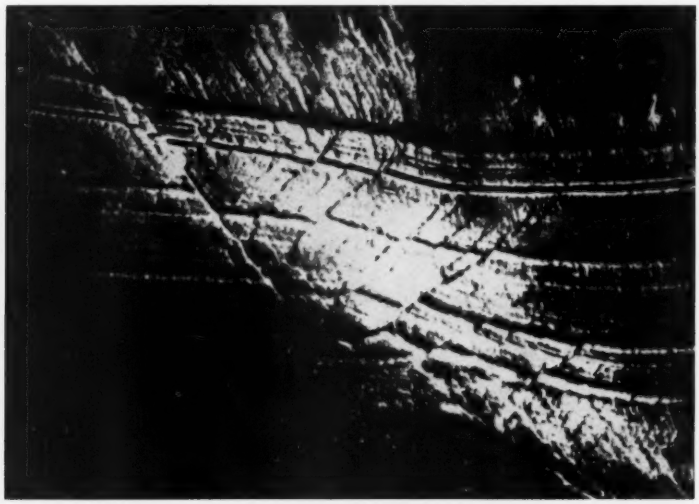


FIG. 10. *Experimental fault in wet clay*, produced by H. Cloos. Horizontal extension is induced by expanding the support. From Bucher (1933).

fault zones of eastern Venezuela. An analysis of this experimental structure might, therefore, be instructive.

The essentials of the experimental arrangement are described by Bucher (1933). They consist of a movable metal sheet placed on a table top, and a cake of wet clay resting partly on the table and partly on the movable sheet. Horizontal extension of the clay is induced by moving the metal sheet. The edge of the sheet acts as a singularity from which the shearing movements expand upward. It is beyond the scope of this paper to discuss the basic questions concerning the energy sources for crustal movements; but both induction of movement from depth and singularities at depth from which shearing spreads upward would appear acceptable geological conditions.

The downthrown side of the experimental fault shows a wide zone of deformation in which there is a complex pattern of ruptures, shears, and rotations. The main fault is the lower boundary of this zone. It is not a simple rupture but a system of original en echelon breaks, now partly communicating. It is composed of segments of shear lines and is, on the average, less steep than the individual shear lines. It consists essentially of three parts: (1) an upper part composed of en echelon breaks with, on the average, low dip; (2) a central, steeper part; and (3) offset en echelon, a lower flatter part. The low-dip segments exhibit drag on the downthrown side with a minimum of throw. The steeper central part shows no drag, even a hint of reverse drag, and a maximum of throw.

Within the zone of deformation the system of smaller faults dipping opposite to the main fault is of special interest. They usually split up in breaks arranged en echelon as they approach the limit of the zone of deformation, where they disappear. Also along these small faults variable displacement may be observed. Where they split up and die out the displacement grades into plastic warps. These faults show then, on a smaller scale, a repetition of the phenomena observed in the main fault zone.

Some of the experimental observations are directly applicable to the actual faults. In the Araibel wells reverse drag with maximum throw was recorded where only one fault break is present (Figure 4). Lower in the section where the fault splits up (Figure 5), the cumulative throw has decreased. Kamen-Kaye (1953) reports from the Las Mercedes field in the western part of the basin that pronounced reverse drag with a maximum of throw coincides with the steeper part of the faults, which are concave-upward. Throw decreases with depth where faults become flatter. It should be noted that these faults occur in the same basin, but that the Tertiary section is reduced by erosion (Mencher et al., 1953, Renz et al., in press); only the lower parts of the type of fault structures fully preserved farther east are present.

Mechanical Interpretation of the Fault Zones

Intuitively, the troughs with their zones of reverse drag are interpreted as slump troughs due to gravitational slumping as the walls of the fault pulled

apart (Kamen-Kaye, 1953). Actually, the downthrown block as a whole can be considered as a slump because it moved under the influence of gravity. Within the downthrown block the troughs and zones of reverse drag are just areas of more than average gravitational movement or slumping, just as the zones of normal drag are areas of reduced gravitational movement. Such fluctuations are necessarily associated with the geometry of the fault breaks, whose inclination also fluctuates around the average dip. Along the steeper parts of the fault vertical movement must be larger for equal horizontal extension. In addition, opposition to movement—friction—is greater along the flatter parts or those where the fault splits up into a series of en echelon breaks. In these flatter parts the hanging block responds later to horizontal extension and drag develops.

The results of the foregoing discussion can be summarized as follows: We visualize the fault as a zone of shearing deformation grown upward from depth. The main fault break formed first as a system of discontinuous surfaces of shear which entered in partial communication as movements continued. These breaks grew and spread upward simultaneously with the growth of the zone of shearing deformation. Between the main breaks and the remainder of the zone of deformation there was thus continuous interaction throughout the period of fault growth. It defined the shape of the main fault and simultaneously the associated structure of the zone of plastic deformation.The mode of deformation and the sedimentary section affected by it were similar for large parts of the basin. This would explain the fact that the structural plan of all the fault zones considered is basically similar.

As plastic deformation affects the microstructure of the rocks, it should have an influence on seismic velocities. It would appear that there is a maximum of this deformation in the center of the slump troughs. The amplitude of the troughs decreases upward, so there is a slight increase of section in their central part. This may be due partly to syntectonic sedimentation and partly to plastic deformation.

SEISMIC DISTORTIONS OF REFLECTIONS FROM BELOW THE FAULT

Such a fault zone, then, is the model in which the propagation of a seismic pulse is to be studied. It is complex, and the analysis will have to be restricted to effects of primary importance for reflection seismology; that is, to an explanation of the basic distortion pattern actually observed in all the fault zones. The distortion consists of an apparent repetition of the structures above the fault and is thus gradually changing across the fault zone. This circumstance requires the consideration of continuous wave fronts rather than individual ray paths. The problem can be approached in two steps by analyzing (1) the influence of the fault zone on the velocity distribution, and (2) the influence of this velocity distribution on a seismic wave. The second step would imply the construction of successive wave fronts by means of the Huygens principle, from the initiation of the wave at the shot point throughout its entire development. This is practically impossible for complex velocity distributions. For our essentially qualitative

considerations, however, some simplifications are indicated. The initial distortion may be approximated by an analysis of vertical travel times. To this initially distorted wave front the Huygens principle can be applied under the assumption of a constant velocity, and the further development of the wave can be studied.

Velocity Distribution and Vertical Travel Times in a Fault Zone

The influence of the fault zone on the velocity distribution is twofold. It consists of (1) displacement of velocity strata, possibly with thickening of some of the strata on the downthrown side due to syntectonic sedimentation; and (2) plastic alteration of the rocks in the zone of structural deformation.

In order to study the first effect quantitatively, a simplified model of a fault zone is drawn in Figure 11. The model contains the characteristic features described above for the upper part of the real fault zones. There is a slump trough

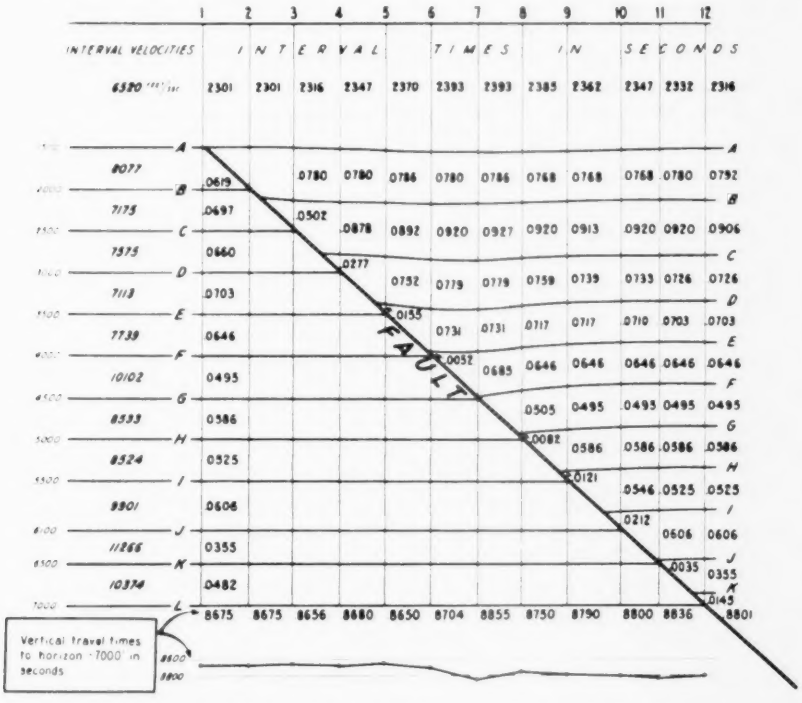


FIG. 11. *The effect of fault displacement of velocity layers on vertical travel times.* Interval velocities on the up-side (Column 1) correspond to Cantaura-1 velocity survey. On the downthrown side stratigraphic intervals (for instance, *BC*) are assumed to have the velocity of the corresponding interval (*BC*) on the up-side. The sum of the interval times for each column, representing the vertical travel time to horizon −7,000 feet, is shown at the base of the figure.

on the downthrown side with a width of about 6,000 feet and an amplitude reaching 200 feet. The fault has a maximum throw of 500 feet in the center of the trough and dies out in the higher part of the section. Beds on the upthrown side are assumed to be flat. On the downthrown side the upper part of the section (between horizons D and A) is increased by syntectonic sedimentation. The section is subdivided into intervals of constant velocity. The intervals correspond, for the upthrown side, exactly to the data obtained from the well velocity survey of the Socony well, Cantaura-1, which is located a few kilometers west of the Araibel wells. For the downthrown side velocity intervals are considered equivalent to stratigraphic intervals. The position of the slump trough in the stratigraphic sequence corresponds approximately to the conditions in the Araibel fault zone. The distorting effect of this velocity distribution on a seismic wave may be approximated by analyzing the vertical travel times to a horizon underneath the fault, as shown in Figure 11. It may be concluded that the main effect of fault displacement and syntectonic sedimentation on the seismic wave is a retardation in the fault zone. This is because in each column the fault cuts out a part of the section and replaces it by masses faulted down from a higher part of the section with generally lower velocities. This effect has a maximum in Column 7 where the fault eliminates the 10,102 ft/sec section and replaces it by material with velocities ranging from 6,520 ft/sec to 8,077 ft/sec.

If we replace this velocity distribution by a smooth one corresponding to a linear velocity increase with depth and apply it to the same fault model (Figure 12) the retardation is still present but less conspicuous. The fact that in the center of the slump zone the fault has a maximum of throw shows up as a slight maximum in the curve of vertical travel times.

This simplified model avoids the complications of regional dip varying with depth, as present in the eastern Venezuelan basin. Often the effect of the faults on this regional dip is only local; it becomes negligible if points several miles apart are considered. For the vertical travel times this means that there is a regional gradient across the fault zone, and a superimposed local maximum for a column through the slump trough.

The foregoing discussion demonstrates that vertical travel times in a fault zone vary from point to point. Given a perfectly linear velocity increase with depth in the unfaulted section, the variations of vertical travel times in the faulted section follow a smooth curve which has a maximum in a column through the center of a slump zone (Figure 12). Actual velocity-depth curves, however, fluctuate around the smooth mathematical curve, and the same will be true for the relationship between the actual curve of vertical travel times and the smooth one. The smooth curve may be considered as the basic effect; it is present in all fault zones corresponding to our model. The superimposed fluctuations vary from case to case. If the actual velocity distribution does not approximate a linear increase with depth; if, for instance, there is a sudden increase of velocity in one part of the section, as shown in Figure 11, these fluctuations may become of

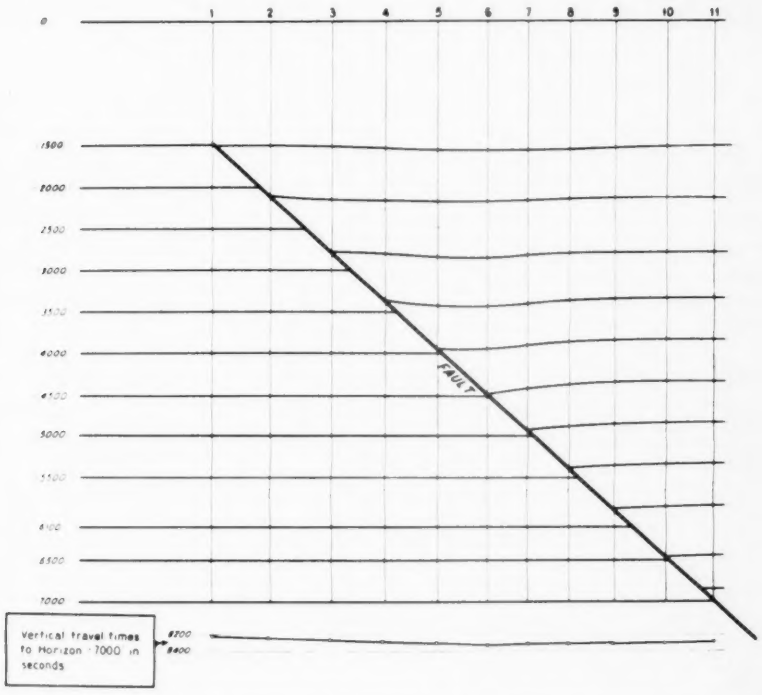


FIG. 12. *The effect of fault displacement on vertical travel times for linear increase of velocity with depth.* $V = V_0(1+kh)$, $V_0 = 2060$ m/sec, $k = .000265$/m. On the downthrown side average velocities from the surface to the fault are assumed identical to those for equivalent stratigraphic intervals on the up-side.

primary importance. The interval velocities used in Figure 11 increase rather suddenly at −4000 feet. It happens that this change coincides with the center of the slump zone. The main fluctuation is thus in phase with the smooth curve; it enhances its effect.

The second effect of faulting on velocity distribution, plastic deformation, is hard to judge, and we are limited to rather vague conjectures. In a general way we may expect that this deformation reduces velocities for two reasons: (1) It may be assumed that sedimentation and compaction leave the individual grains composing the sediments in a state of closest packing; that is, pore space would be at a minimum, and any relative dislocation of the grains with respect to each other would increase the pore space (cf. the discussion of dilatant flow by Green, 1950, p. 78). Furthermore, additional small voids develop during plastic deformation, even under compression, as mentioned by Nádai (1950, p. 419,

footnote). Both effects would tend to decrease velocities. (2) Much of this plastic deformation probably consists of movements along minute shear and cleavage fractures (Nádai, 1950), which loosen the bonds between rock particles and thus tend to decrease velocities. These effects may be lessened by post-deformational recrystallization, but it seems reasonable to expect an overall decrease of velocity in the plastically deformed parts of the section. From the geometrical picture of our fault zones it would appear that there is a maximum of plastic deformation and consequently a maximum seismic retardation near the center of the slump troughs. The effects of fault displacement and of plastic deformation would be additive. The local maximum of vertical travel time in the column through the center of the slump trough would be emphasized, and local fluctuations due to a particular velocity-depth curve would be less important.

Development of a Distorted Wave

The approximate distorting effect of such a velocity distribution and consequent distribution of vertical travel times on a seismic wave front is shown in

FIG. 13. *The distortion of a circular wave front by a fault zone.* The points on the wave front are assumed to be delayed by the amounts computed in Figure 11, in material with a velocity of 10,000 ft/sec.

Figure 13. It is assumed that the wave front is subject to the delays computed in Figure 11 for vertical travel paths, in material with a velocity of 10,000 ft/sec. In this case the distorted wave front has a cusp; that is, it splits up in two different convex-forward wave fronts, with the cusp as a source of diffraction.

The further development of such a distorted wave front is approximately depicted in Figure 14 by application of the Huygens principle. After reflection there is a second distortion affecting each one of the partial wave fronts while they pass upward through the fault zone (Figure 15). Hypothetically, then, there might be four emerging partial wave fronts with their diffraction fronts crossing each other; they would be recorded on the surface as complex interferences. Of these, Reflection A, marked by a heavy line in Figure 15, is of primary importance for a geophone spread of conventional length; it is the first reflection recorded from a particular horizon, and it ties to the less distorted

reflection recorded at the next shot point on the right. Furthermore, if the initial distortion were gradational, without a cusp, then the interferences would become less conspicuous or disappear entirely, and Reflection A would be the only one recorded. This reflection dips to the left. Its dip is not that of the flat reflector below the fault but that of reverse drag in the deformation zone above the fault.

If the shot point were assumed to be on the left side of the slump trough, a somewhat symmetrical picture would be obtained. The reflection corresponding

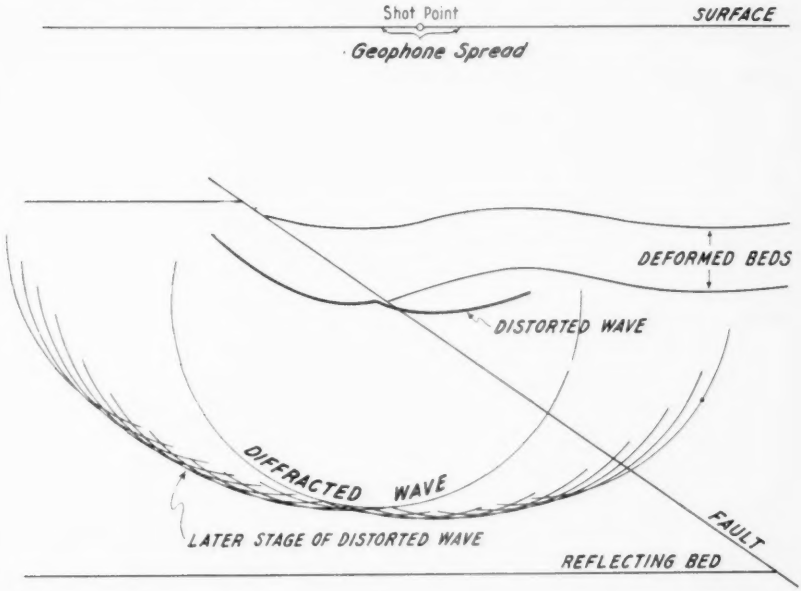


FIG. 14. *The development of the distorted wave front,* with the shot point slightly to the right of the center of the slump trough. For a constant velocity interval subsequent stages of the wave front are obtained as the envelope to circular elementary waves, according to the Huygens principle. Note that the cusp is a center of diffraction for the two partial convex-forward wave fronts.

to "A" on Figure 15 would dip to the right. Altogether, then, a series of seismic records obtained in the fault zone will show distorted reflections from a plane horizon underneath the fault. The reflections will not depict this plane reflector, but the configuration of the zone of structural deformation through which the wave had to travel. In addition, if the distortion is sufficiently severe, a complex pattern of interferences may obscure the reflections from underneath the fault. It should also be noted that the distortion decreases the radius of curvature for the individual partial wave fronts and is accompanied by a diffraction pattern.

We get an overall picture of the distortion if we replace the series of circular waves by a plane wave as shown in Figure 16. Distortion is assumed to be relatively mild in this case. The development of the wave front is illustrated again

by applying the Huygens principle. The distorted wave front does not have a cusp but a smooth concave-forward segment. However, this segment has a buried focus, and interferences develop. The recorded wave front depicts the slump troughs of the fault zone through which it traveled.

These are the basic distortions. They should be observed everywhere for similar geological models. Superimposed on these effects are fluctuations which may vary from case to case. When these fluctuations affect only a small part of

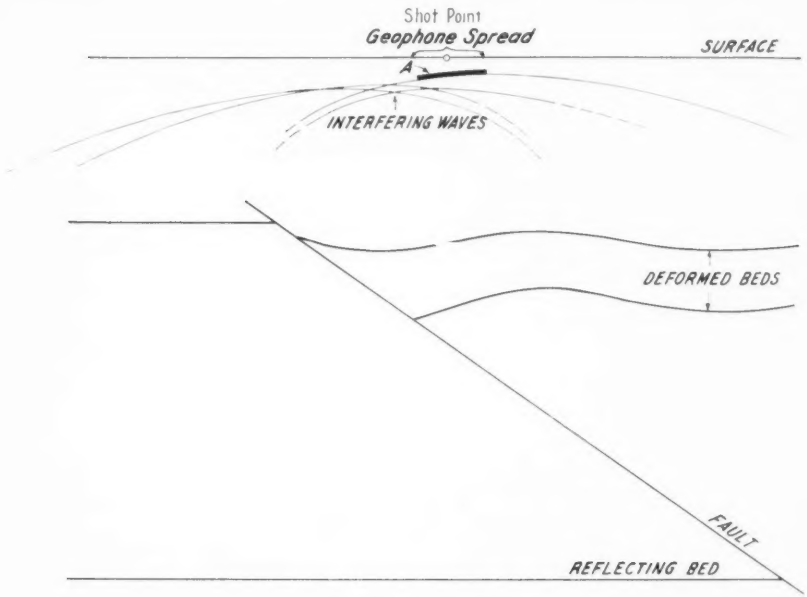


FIG. 15. *The development of a distorted wave front after reflection.* Each partial convex-forward wave front is distorted a second time, and four partial wave fronts may emerge at the surface and be recorded as interferences. Segment *A* of the wave front, marked with a heavy line, is the most important reflection. The diffraction pattern (shown by dashed lines) is not fully represented.

the wave front (small as compared with the wave length, which is of the order of 300 feet), then they should not disturb the seismic wave appreciably.

APPLICATIONS AND CONCLUSIONS

Seismic data from fault zones in the eastern Venezuelan basin are complex. They may be divided into two groups: (1) Reflections from above the fault, representing true geological structures, and (2) Reflections from below the fault, which are affected by seismic distortions. For a better understanding of the structures above the fault a broadened concept of faulting is proposed: Faults are three dimensional bodies of plastic deformation, not just two-dimensional sur-

faces of slippage. The actual fault breaks, though essential, form only one part; they are the lower boundary of the zone of deformation. This fault body acts as a distortion lens for seismic waves. Its structure offers a reasonable explanation for the seismic distortions observed for reflections from below the fault.

These considerations have a practical significance for two main reasons:

(1) Seismically, the fault zone—the zone of plastic deformation—is often a much more conspicuous phenomenon than the actual fault break. The deforma-

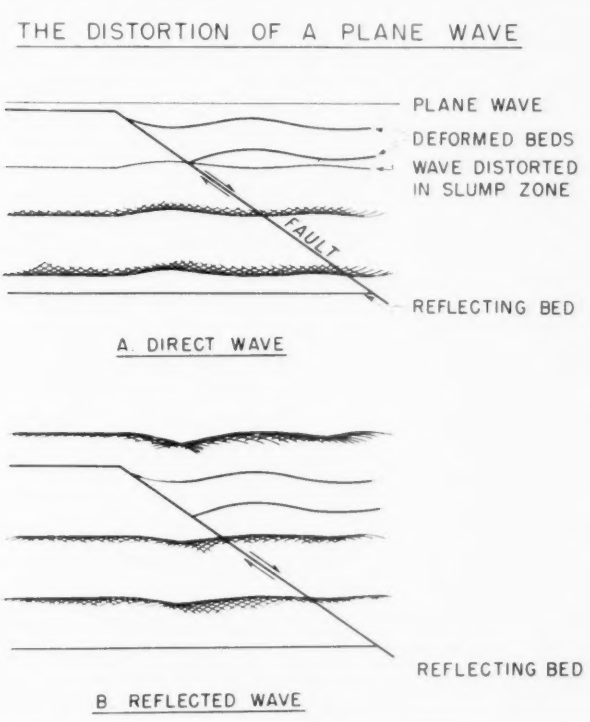


FIG. 16. *The distortion of a plane wave in a fault zone.* Initial distortion is assumed to be smooth. Subsequent stages in the development are obtained by application of the Huygens principle. Interferences of the reflected wave result from buried focus of concave-forward part of wave front. Compare with distorted reflection *D* on Figures 6 and 7.

tions and distortions occurring in this zone are often the first abnormalities noticed on a seismic line. It may thus be possible to infer faults from the mere presence of these features. This is especially important in areas where there are no characteristic reflections and the usual method of character correlation fails, or where character correlation is ambiguous and supporting evidence is needed. This point may be illustrated by a brief case history of the Araibel fault. Figure 17

shows a map prepared in 1945 from comparatively poor seismic data, covering the area rather loosely. The large Araibel fault shown on Figures 2, 3, 4, 5, and by a heavy dashed line on Figure 17, was not found at the time; but the map shows the deep slump trough distinctly. A seismic interpreter, aware of the meaning of this feature, would correctly infer a fault, and a closer inspection of the behavior of different horizons across this fault would also reveal the direction of

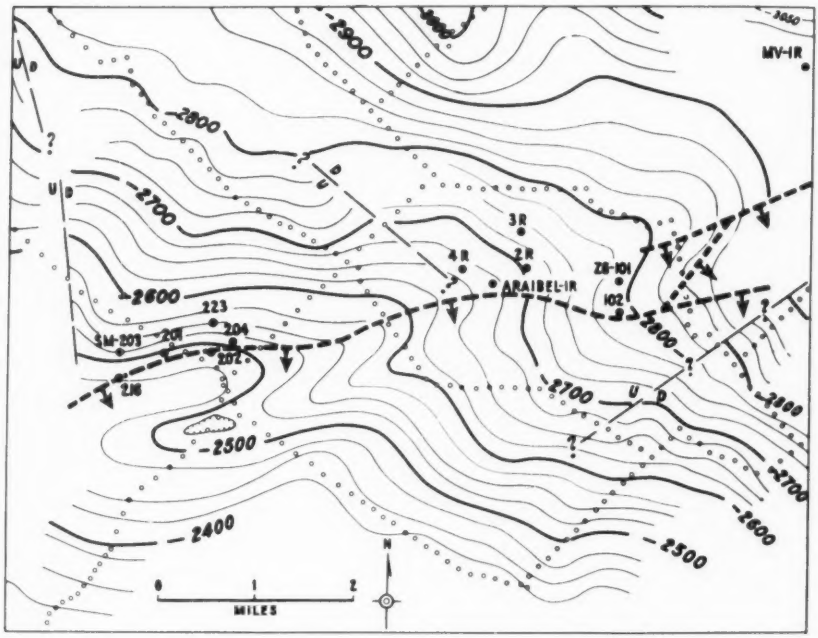


FIG. 17. *Early seismic map of the Araibel area* on a horizon in the central part of the sedimentary section, prepared in 1945. Depths are in meters subsea. The Araibel fault, missed at the time, is shown (heavy dashed line) as found by subsequent seismic shooting and deep drilling. The deep slump trough is clearly visible.

throw. All this is possible without character correlation. The fault structures along the Araibel fault, however, are particularly clear; and most of the smaller faults are accompanied by considerably more moderate deformations, such as shown on Figure 6. Many of these structures will be of the same magnitude as observational and computational errors, or fluctuations in reflection times due to a structurally meaningless irregular velocity distribution in the shallow subsurface; and the interpreter is confronted with a problem similar to that of recognizing a reflection which barely emerges above the background noise on the record. Such a reflection cannot be detected on a single trace, but can often be recog-

nized across the entire record because of the regular line-up. Translated into terms of the detection of fault structures, this means that we may often doubt the reality of a structure on an individual line; but the probability of its reality is greatly enhanced if the same structure occurs on a number of lines, forming a structural trend on the map. In addition, "background noise" on the map may be reduced by special care in the computations of corrections, and by a number of observations and considerations involving the regional geology. Especially effective is the comparison with very shallow reflections, if present, which are structurally deformed only slightly if at all and therefore may give reliable information about the presence of computational errors.

(2) The correct interpretation of structural and seismic deformations in fault zones is one of the main problems of seismic exploration for oil in many basins. The structural deformations may contain accumulations of oil, as demonstrated by the Boca Field. The purely seismic distortions may simulate faults and structural closure which do not exist and obscure at the same time real branch faults and closure.

Similar phenomena were reported from the Texas Gulf Coast by Quarles (1951). The occurrence of these apparently erratic and unpredictable distortions caused Romberg (1952) to be rather pessimistic about seismic prospecting in fault zones in general. The distortions in the Eastern Venezuelan basin, however, complex though they are, follow a regular pattern. They are predictable, at least qualitatively, and for effects of first magnitude. A qualitative allowance can be made for this part of fault distortion, and the approximation of interpretation to the actual structural picture can be improved.

ACKNOWLEDGMENTS

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GEOPHYSICS, VOL. XXI, NO. 2 (APRIL, 1956), PP. 388–405, 10 FIGS.

A PRELIMINARY EVALUATION OF THE SHALLOW REFLECTION SEISMOGRAPH*

L. C. PAKISER† AND R. E. WARRICK†

ABSTRACT

Following successful tests of a specially constructed shallow reflection seismograph in early 1954, new experimental work has been conducted on the Colorado Plateau, in the Upper Mississippi Valley zinc-lead district, and in Portage County, Ohio. Although reflections were recorded in all of these areas, they were not continuous and correlatable on the Colorado Plateau and in the Upper Mississippi Valley. In Ohio, on the other hand, reflections were recorded from horizons within the Pleistocene overburden as well as from bedrock and horizons within the consolidated rock section. Conditions favoring good reflections are similar for both shallow- and deep-reflection work; they differ only in scale.

INTRODUCTION

The shallow reflection seismograph is a new development in the art and science of geophysical exploration. It was introduced by the U. S. Geological Survey during 1954 and has already been tested in a wide variety of oil, mining, and ground water exploration problems (Pakiser and Mabey, 1954; Pakiser, Mabey, and Warrick, 1954; Olson, 1955). The mining exploration problems for which it was designed remain largely unresolved.

Many near-surface problems in oil exploration can be solved with the shallow reflection seismograph. These include shallow structural investigations and problems of datum reduction in conventional reflection seismology. But the most important—and surprising—result of these recent developments has been the demonstrated usefulness of the higher frequencies of the spectrum at depths of several thousand feet (Olson, 1955). This high resolving power at intermediate depths should prove to be of great value in mapping the small, hard-to-find structural and stratigraphic features that have been overlooked in conventional seismic reflection operations.

The U. S. Geological Survey successfully tested a specially constructed portable shallow reflection seismograph in Osage County, Oklahoma, and Rice County, Kansas, in March and April, 1954 (Pakiser, Mabey, and Warrick, 1954). Following this demonstration of the possibilities of the shallow reflection seismograph under nearly ideal conditions, more experimental work was done on the Colorado Plateau, in the Upper Mississippi Valley zinc-lead mineralized district, and in Portage County, Ohio. Although reflections were recorded in all of these areas, they were not continuous and correlatable on the Colorado Plateau and in the Upper Mississippi Valley. In Ohio, on the other hand, reflections were recorded from horizons within the Pleistocene overburden as well as from the sur-

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† U. S. Geological Survey.

face of the bedrock and from horizons within the consolidated rock section.

The results of these tests of the shallow reflection seismograph on some typical problems of the U. S. Geological Survey are described in this paper.

INSTRUMENTS AND FIELD METHODS

The 12-channel portable reflection seismograph used in these tests has the following characteristics:

The filtered frequency range of the amplifiers is 75 to 300 cycles per second; the refraction setting uses a low-frequency cut off of $7\frac{1}{2}$ cycles per second. The instruments feature fast-acting automatic gain control and variable presuppression control.

The paper speed of the oscillograph is 25 inches per second; the smallest timing-line interval is 2 milliseconds; the galvanometers, damped 70.7 percent of critical, have a natural frequency of 500 cycles per second.

Conventional geophones were used in the initial tests; they were replaced by higher frequency geophones (natural frequency, 40 cycles per second) for the later work.

Conventional field methods with both hole and single air shots and short in-line and split spreads and conventional computing procedures were used.

RESULTS OF EARLY WORK

During the summer of 1953, in the course of routine seismic refraction studies in the Monument Valley of Arizona and Utah, erratic arrivals were noted on the first few geophones of a conventional refraction spread. They were tentatively identified as reflected arrivals when plotted on a travel-time curve. This identification was confirmed by shooting short spreads in the zone of erratic arrivals (see Figure 1). This phenomenon was observed in a typical Triassic channel area with the Shinarump conglomerate of Late Triassic age forming the cap of a mesa and with the Moenkopi formation of Early Triassic age (mudstones and siltstones) at a depth of about 40 feet. An unconformity separates the two formations. Several feet of loose dune sand are at the surface. The velocities in the Shinarump and Moenkopi formations are known from the refraction data to be about 4,500 and 12,000 feet per second respectively.

The travel-time curves of the reflected arrivals as recorded and as shown in the upper left hand part of the figure are strikingly like text book examples of reflection travel-time curves. For comparison, V_1 and V_2 segments (representing the Shinarump and Moenkopi formations) have been reconstructed on the basis of nearby refraction data. Although suggestions of these direct and refracted arrivals are seen on the original seismograms they have been so sharply attenuated that the reflected arrivals are, in effect, the first arrivals. At every geophone, except the first one, the reflected arrivals precede the air wave.

The depth points for each reflected arrival describe a plane surface at a depth

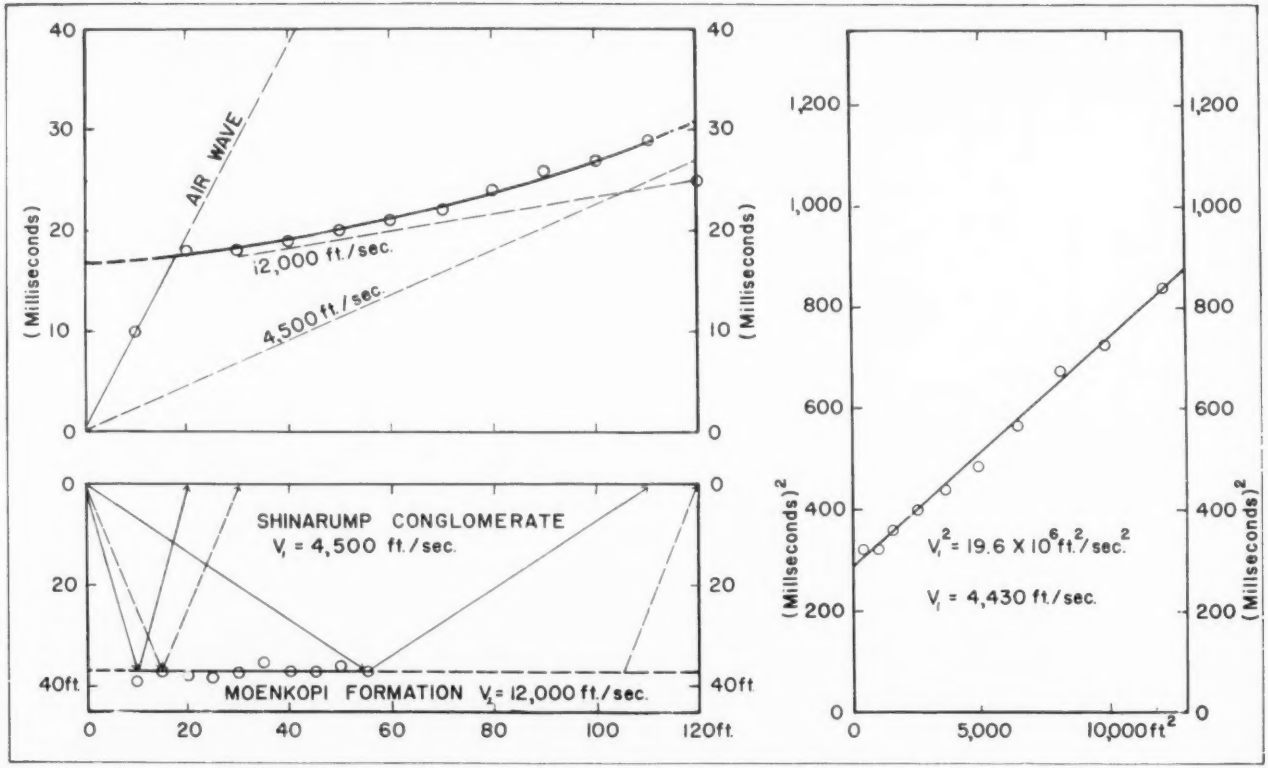

FIG. 1. Analysis of reflected arrivals, Monument Valley area.

of 37 feet, which is in good agreement with that obtained from refraction shooting (lower left-hand part of figure).

The velocity derived from a plot of the squares of the horizontal distances and arrival times is 4,430 feet per second, an excellent agreement with the Shinarump velocity determined from the refraction travel-time curves (right-hand part of figure).

Finally, a spread shot in the opposite direction displayed the same characteristics, which would seem to rule out changes in the thickness of the near surface low velocity layer as the cause of the erratic arrivals. Undoubtedly this was an accident, but it did stimulate our interest in the possibility of using the reflection seismograph at really shallow depths.

In Osage County, Oklahoma, air shooting using the broad frequency band of 75 to 300 cycles per second gave useful shallow information. On one seismogram (see Figure 2) three clearly defined reflections are identified in advance of the air

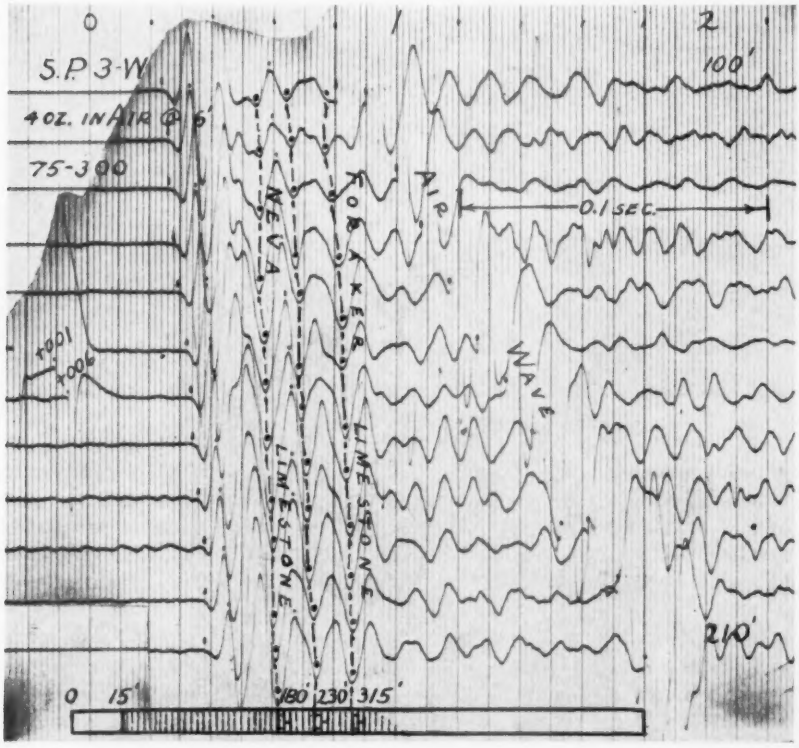

FIG. 2. Shallow reflection seismogram from air shot, Osage County, Oklahoma, and computed geologic section.

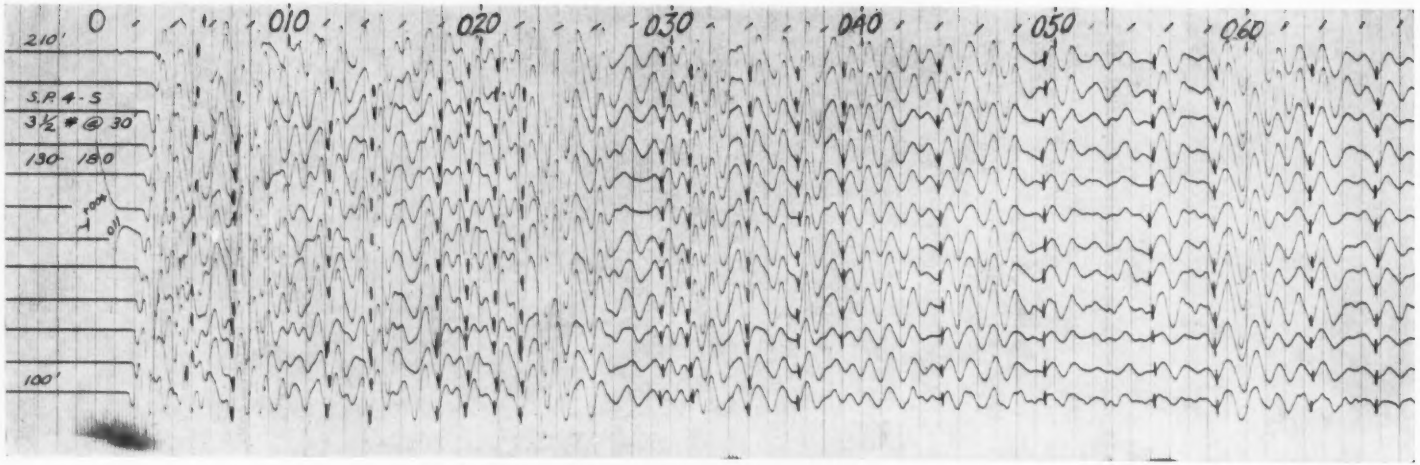

FIG. 3. High-frequency reflections through 3,500 ft of section, Osage County, Oklahoma.

wave, which strikes geophone No. 1 at 81 milliseconds from the shot moment. The Neva limestone of Permian age yields the first reflection at 55 milliseconds from the shot moment. It is about 180 feet deep. The Foraker limestone of Permian age yields the third reflection at 78 milliseconds. It is about 315 feet deep. A single 4-ounce charge was fired from a height of 6 feet. The geophone spacing was 10 feet with the first geophone 100 feet from the shot point. Reflection arrivals are timed from the instant the air wave strikes a geophone on the surface of the ground at the shot point.

A seismogram obtained from a nearby shot point displays prominent reflections out to 700 milliseconds or about 3,500 feet (see Figure 3). Some of the

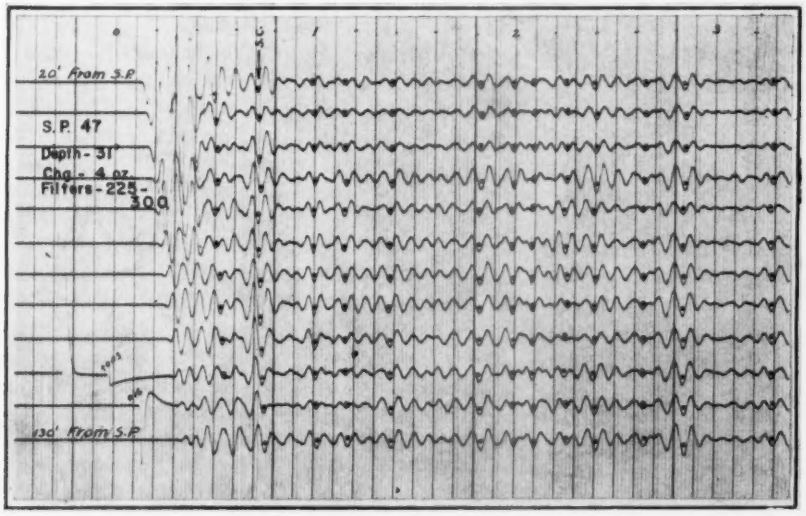

FIG. 4. Shallow reflection seismogram, Rice County, Kansas.

later reflections on this seismogram, and those reproduced in Figures 4 and 8, may be multiple reflections. The short spreads prevent positive identification of multiple reflections. The charge here was $3\frac{1}{2}$ pounds, fired from a shot hole 30 feet deep, below the base of the low velocity "weathered layer." The spread was the same as that for the previous shot and the filter band was 130 to 180 cycles per second.

In Rice County, Kansas, the Stone Corral dolomite of Permian age, and a large number of horizons at greater depths, gave excellent closely spaced high-frequency reflections. To obtain the seismogram illustrated in Figure 4, a charge of 4 ounces was fired from a depth of 31 feet below the weathered layer. The filter frequency band was 225 to 300 cycles per second. The first geophone was 20 feet from the shot point and the remaining 11 geophones were spaced outward at 10-

foot intervals. A prominent reflection was recorded at 74 milliseconds from the Stone Corral dolomite. There are 11 more reflections (or multiple reflections) below the Stone Corral in a depth interval of about 1,500 feet.

COLORADO PLATEAU EXPERIMENTS

Shallow seismic reflection experiments were conducted in three areas on the Colorado Plateau during the summer of 1954, as a part of the U. S. Geological Survey's program on behalf of the Atomic Energy Commission. Field work was done at Nokai Mesa, along the Arizona-Utah boundary in the Navajo Indian reservation; at Deer Flat, near the eastern end of White Canyon in San Juan County, Utah; and at Monogram Mesa in southwestern Montrose County, Colorado.

Nokai Mesa was chosen as the original Colorado Plateau test site because adequate control information was available from drilling and from a previous seismic refraction survey (Wantland and Casey, 1952). By shooting in selected drill holes Wantland and Casey of the Bureau of Reclamation had determined that the velocity in the Shinarump conglomerate ranges from 5,000 to 7,300 feet per second. The velocity in the Moenkopi formation as measured in drill holes ranged from 10,800 to 15,800 feet per second.

The Shinarump conglomerate at Nokai Mesa crops out or is covered by a few feet of sandy soil. It ranges in composition from fine-grained sandstone to conglomerate, and is 70 to 160 feet thick at the test site. Uncomformably below the Shinarump conglomerate is the Moenkopi formation, composed of siltstones and mudstones in thin horizontal layers. The surface of the Moenkopi formation had been eroded by stream action before, or during, deposition of the Shinarump and there is a channel 40 feet deep and about 900 feet wide at the test site. Uranium ores are found in some parts of the Shinarump conglomerate in these channels in the Monument Valley.

In the field work at Nokai Mesa spreads of geophones spaced 10 feet apart with short offsets from the shot were used. Air, surface, and hole shots were used. Best results were obtained when holes from a few to 30 feet deep, fluid tamping, and charges of 8 ounces of dynamite were used. There was some evidence of reflections coming from the Shinarump-Moenkopi contact, but the quality was low, many of the reflections bordering on the indiscernible.

One of the better Nokai Mesa seismograms is illustrated in Figure 5. The first geophone here was placed 20 feet from the shot point. Eight ounces of dynamite were fired from a hole 3 feet deep and the filters were set for the 170-300 cycles-per-second band. A weak reflection, which probably came from the Moenkopi, is marked at 53 milliseconds from the shot moment. Reflected energy is also noted from greater depths. (The fifth trace was dead and has been cut out of the seismogram.)

At Deer Flat, a sandstone member of the lower unit of the Chinle formation of Late Triassic age locally called Mossback, crops out or is covered by sandy

soil ranging up to 20 feet thick. The so-called Mossback sandstone at Deer Flat is composed of sandstone with mudstone and conglomerate lenses and is about 70 feet thick. Beneath the so-called Mossback is about 140 feet of mudstone of the Chinle formation, which also includes interbedded sandstone, clay, and conglomerate. Beneath the Chinle at Deer Flat there is from 0 to 40 feet of the Shinarump conglomerate, consisting predominantly of sandstone with mudstone and con-

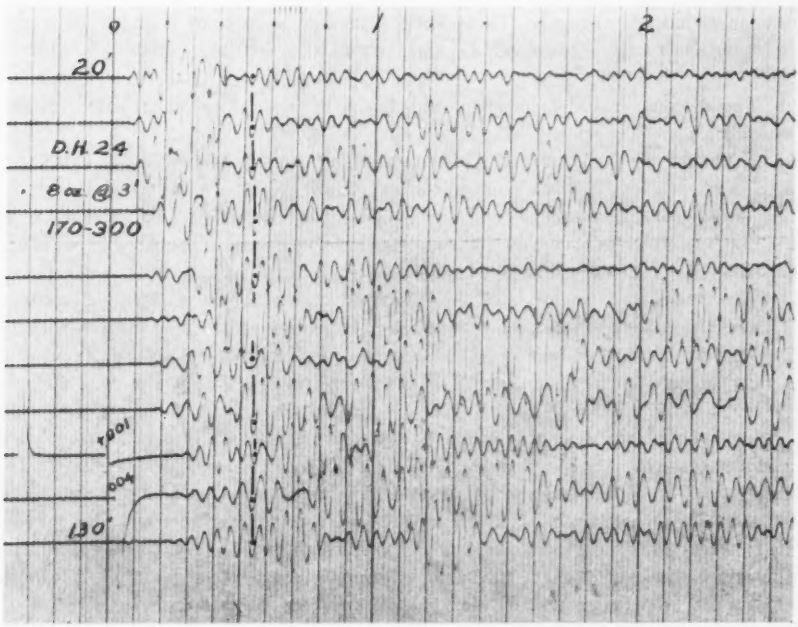

FIG. 5. Shallow reflection from Moenkopi formation, Nokai Mesa, Arizona.

glomerate lenses. The Moenkopi formation unconformably underlies the Shinarump conglomerate. At Deer Flat the Moenkopi formation is about 300 feet thick and is predominantly thin-bedded mudstone, with some sandstone layers.

At Deer Flat the objective was to determine if the Shinarump-Moenkopi interface could be mapped by means of seismic reflections. The seismic refraction method, which has been successfully used in channel areas where the Shinarump conglomerate is at the surface, is of limited value in the so-called Mossback and other Chinle-covered areas because the velocity in the Chinle mudstones greatly exceeds the velocity in the Shinarump conglomerate, and may approach the velocity in the Moenkopi formation.

Both air shots and shallow hole shots were tried at Deer Flat; the best records were obtained from hole shots 10 to 30 feet deep, loaded with 8 ounces of dyna-

mite. Usually the No. 1 geophone was offset from the shot point by 20 feet and a 10-foot geophone spacing was used, although some experiments with longer offsets were conducted. At a few shot locations near a core hole, reflections were observed at a time which corresponds closely to what would be expected for the Shinarump-Moenkopi contact. The reflection quality was poor and reflections could not be correlated from shot point to shot point. Many strong reflections appeared on a few traces and then either disappeared completely, or the stepout time changed abruptly. These abrupt changes in stepout time are believed to be caused by diffraction from angular irregularities on the surface of the Moenkopi.

The seismograms at Deer Flat were similar to those from Nokai Mesa shown in Figure 5.

The third area investigated, Monogram Mesa, is entirely different from the first two test areas on the Colorado Plateau. Here areas of thickening within the Salt Wash sandstone member of the Morrison formation of Late Jurassic age are considered to be favorable for the deposition of uranium ore. It was believed possible that mudstone lenses within the Salt Wash member and the overlying Brushy Basin shale member of the Morrison might act as reflecting horizons. This would make possible the preparation of isopach maps for key intervals within the Salt Wash member to establish areas where the Salt Wash is thick and would thus aid in the discovery of uranium ore and in planning the drilling program.

On Monogram Mesa the Burro Canyon formation of Cretaceous age is the surface rock and it is overlain by a few feet of Quaternary eolian deposits. The Burro Canyon formation is of fluviatile origin and is composed of sandstone with mudstones and siltstones. It is about 250 feet thick at the test site. Below the Burro Canyon is the Morrison formation of Late Jurassic age. It also is of fluviatile origin and has a total thickness of about 750 feet at Monogram Mesa, about equally divided between the Brushy Basin and Salt Wash members.

No vertical velocity information was available at Monogram Mesa, but several refraction profiles yielded near-surface velocities of 4,300 to 6,900 feet per second, and deeper velocities of 8,500 to as much as 17,000 feet per second.

Hole shots with both short offset inline and split geophone spreads with 25 foot geophone spacings were used. Many reflections were noted within the critical depth interval but they could not be correlated from shot point to shot point. Filters using the low frequency cut-off points of 170 or 225 cycles per second favored the reflections.

One record displaying several weak reflections is shown on Figure 6. An 8-ounce charge was fired from a depth of 11 feet and the 225 to 300 cycles-per-second filter band was used. This is a split spread with geophones placed at 25-foot intervals from 50 feet to 175 feet on either side of the shot point. The "first breaks" on the southern half of the spread are marked to explain the irregularities

in the weathered layer thickness which cause irregularities in the reflection arrival times.

At present we cannot report success in using the shallow reflection seismograph to solve any of the uranium exploration problems on the Colorado Plateau. However, we believe that these experiments offer enough promise to justify additional experiments using multiple geophones, pattern shooting, and other special techniques that may overcome some of the difficulties.

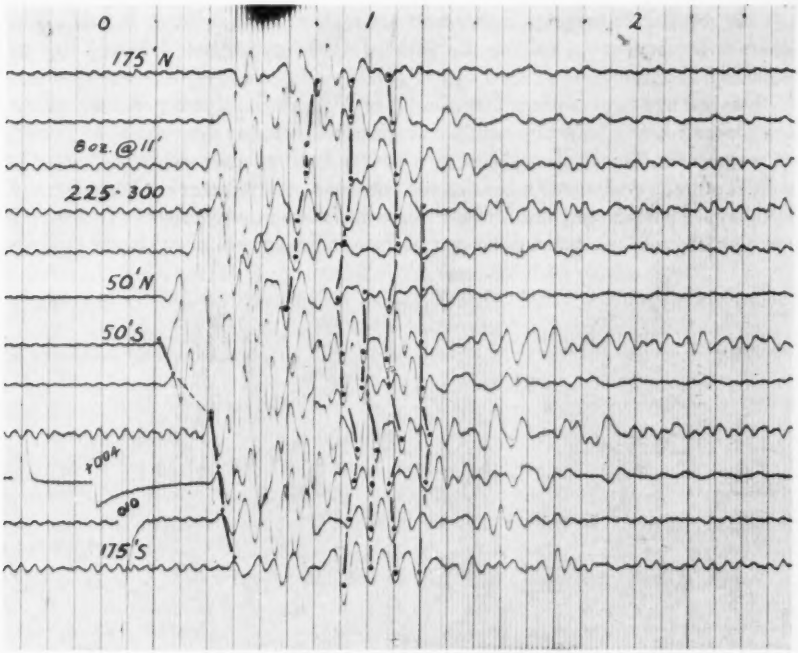

FIG. 6. Shallow reflections from within Morrison formation, Monogram Mesa, Colorado.

Even if good reflections are recorded in the various areas of the Colorado Plateau, many serious, perhaps insurmountable, problems will remain. The near-surface materials are highly heterogeneous and the velocities are known to vary widely over short distances. Mudstone lenses at quite shallow depths undoubtedly act as reflecting horizons and the reflected energy returned from them constitutes "noise" in the usual sense. Shooting conditions are not favorable. The water table is well below the usual shot position and generally below the entire section of interest. There is no low-velocity weathered layer in the classical sense.

The problem of the irregular contact between the Shinarump and Moenkopi

formations has been previously mentioned. Reasonably continuous reflecting horizons with favorable velocity contrasts may not be present in the Morrison formation.

UPPER MISSISSIPPI VALLEY EXPERIMENTS

Late in the summer of 1954, a few weeks of experimental shallow seismic reflection field work was done in the Upper Mississippi Valley zinc-lead mineralized district, in parts of Iowa and Wisconsin which are within driving range of Platteville, Wisconsin. Three test sites were chosen with different surface conditions and different formations underlying the surficial deposits of Pleistocene and Recent loess and alluvium.

The sedimentary section investigated consists predominently of Ordovician and Lower Silurian limestones and dolomites, but there are some shales and sandstones present. These rocks overlie a sequence of sedimentary rocks of Cambrian age. The ore is deposited in the Galena, Decorah, and Platteville formations of Middle Ordovician age, and in the Prairie du Chien group of Lower Ordovician age. Ore deposition is believed to be associated with structure within the Ordovi-

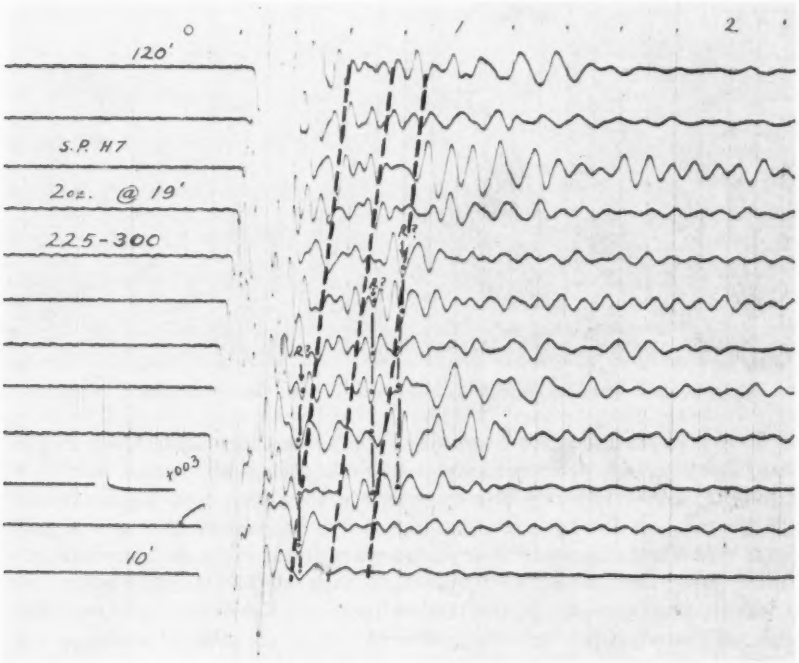

FIG. 7. Multiple reflection of refraction arrivals, Upper Mississippi Valley zinc-lead area.

cian section and the shallow reflection experiments were made in an attempt to map this structure.

The results were doubtful. One problem was that of the multiple reflection of refraction arrivals within the weathered layer (Figure 7). Three dashed lines (Figure 7) parallel to the first arrivals and spaced at twice the weathered layer delay-time are drawn across the seismogram. The first line represents arrivals which have traveled five times through the weathered layer, repeatedly reflected from the surface and the base of the weathered layer, which here is about 10 feet deep and well above the shot position. The weathered layer velocity is about 1,350 feet per second. The sub-weathering velocity is 5,500 feet per second. The charge, shot depth, spread geometry, and filter settings were as shown on the figure.

Arrivals are noted along each of these lines, although they are much more evident on a low-frequency record shot at the same location. This record was selected to show the interference of these arrivals with reflected arrivals. Three partial reflections (?) are marked. The question mark is used advisably, but the reality of the third reflection is accepted. It shows clearly on a travel-time curve, constructed from the low-frequency record, as a deviation along a curved line from the straight line parallel to the first arrivals, just as it does on this figure.

The first 0.1 second on this record, as on others examined, displays a complex interference of repeatedly-reflected refraction and true reflection arrivals, superimposed on the usual noise. Properly spaced multiple geophones may at least partly overcome this difficulty. Mild mixing has helped overcome the problem but it has not eliminated it.

Some reflections were recorded at each of the test sites in the Upper Mississippi Valley but they could not be correlated. Uncertainties in correlated reflection times of only a few thousandths of a second could make the method useless in mapping the small structures in the area because of the high average velocity, and, in addition, the near surface velocity variations cast doubt on the applicability of the method even if perfect reflections were obtained.

The value of the shallow seismic reflection method in exploring for zinc and lead ores in this area is, therefore, doubtful. But these remarks should not necessarily be construed to apply to other zinc-lead districts, where conditions may be more favorable.

PORTAGE COUNTY, OHIO, EXPERIMENTS

During the early fall of 1954, shallow seismic reflection experiments were conducted in the southwestern part of Aurora Township, Portage County, Ohio, to investigate a deep buried valley which contains aquifers that are a major source of ground water. The shallow reflection work was supplemented by refraction profiling and altogether information was obtained from 15 shot points in the area.

In late preglacial time or during one or more of the early interglacial stages of Pleistocene time a deep valley was cut into relatively flat-lying Devonian and

Mississippian rocks (J. D. Winslow,[1] personal communication). Most of the rocks of Devonian and Mississippian age are shale. The Sharpsville and Berea sandstones of Mississippian age are found at elevations of about 950 feet and 800 feet respectively. In modern valleys these sandstones often form prominent benches. The valley was subsequently filled with the glacial drift of later ice advances. There is a surface topographic depression about 2 miles wide and about 200 feet lower than the highland areas on either side of the valley.

The unconsolidated sediments that fill the buried valley are composed of glacial till and coarse glacial outwash materials, and also lacustrine and fluviatile deposits. The lacustrine and fluviatile deposits were laid down in a lake formed when the drainage outlet of the stream was dammed by an advancing ice sheet (Winslow, personal communication).

One detailed shallow seismic reflection profile was run from a drill hole in the deepest part of the valley to near the edge of the valley. Geophone spreads using 25-foot geophone spacings and a 50-foot offset, giving a total spread length of 325 feet, were most commonly used. Continuous profiling was used in the deepest part of the valley. The usual explosive charge was 2 ounces of dynamite fired at a depth of about 20 feet, which is below the shallow water table.

The best results were obtained by using a broad band of frequencies from 75 to 300 cycles per second. Both mixed and unmixed records were taken and the mixing resulted in only slight improvement. Good records were obtained from all of the shot points in the valley, some using only a single electric blasting cap as the explosive charge.

The records were readily correlated across the deepest part of the valley and on to the valley side. Three of these records are reproduced in Figure 8. Prominent reflections are identified for the bedrock and for a number of reflecting horizons within the overlying unconsolidated materials. There are also noted on some of the records a number of reflections (or multiple reflections) below the surface of the bedrock. There is an uncertainty of correlation of one cycle for the bedrock reflection, but the overall configuration of the bedrock surface as determined is considered quite reliable.

A reflection time cross-section for all eight shot points across the deep buried valley was prepared (Figure 9). The reflection times were reduced to a datum elevation of 950 feet. The velocity of the materials immediately below the low velocity weathered layer is 5,500 feet per second. The average velocity of the unconsolidated Pleistocene sediments is estimated to be 6,000 feet per second. The total length of the section shown is about 7,700 feet.

A geologic cross-section was constructed from the reflection time cross-section (Figure 10). The section is controlled at the west end by bore hole information. The seismic reflection information has been supplemented at the east end by refraction data which established that the bedrock is flat in the immediate vicinity of Shot Point 8, and begins dipping downward about 600 feet from the shot point.

There is an excellent correlation of the bedrock reflection and the bedrock as

[1] U. S. Geological Survey.

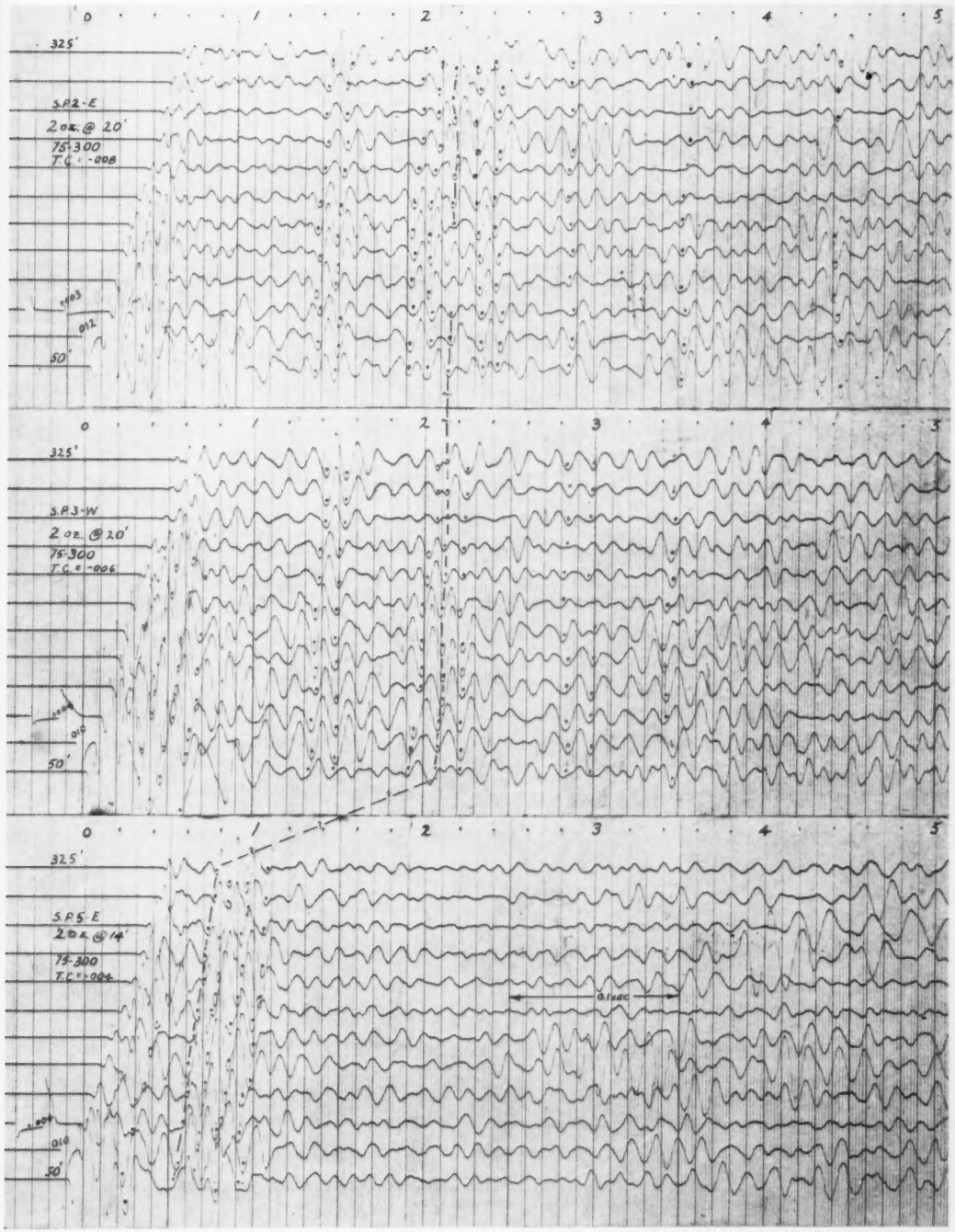

FIG. 8. Correlation of shallow reflection seismograms across buried valley, Portage County, Ohio.

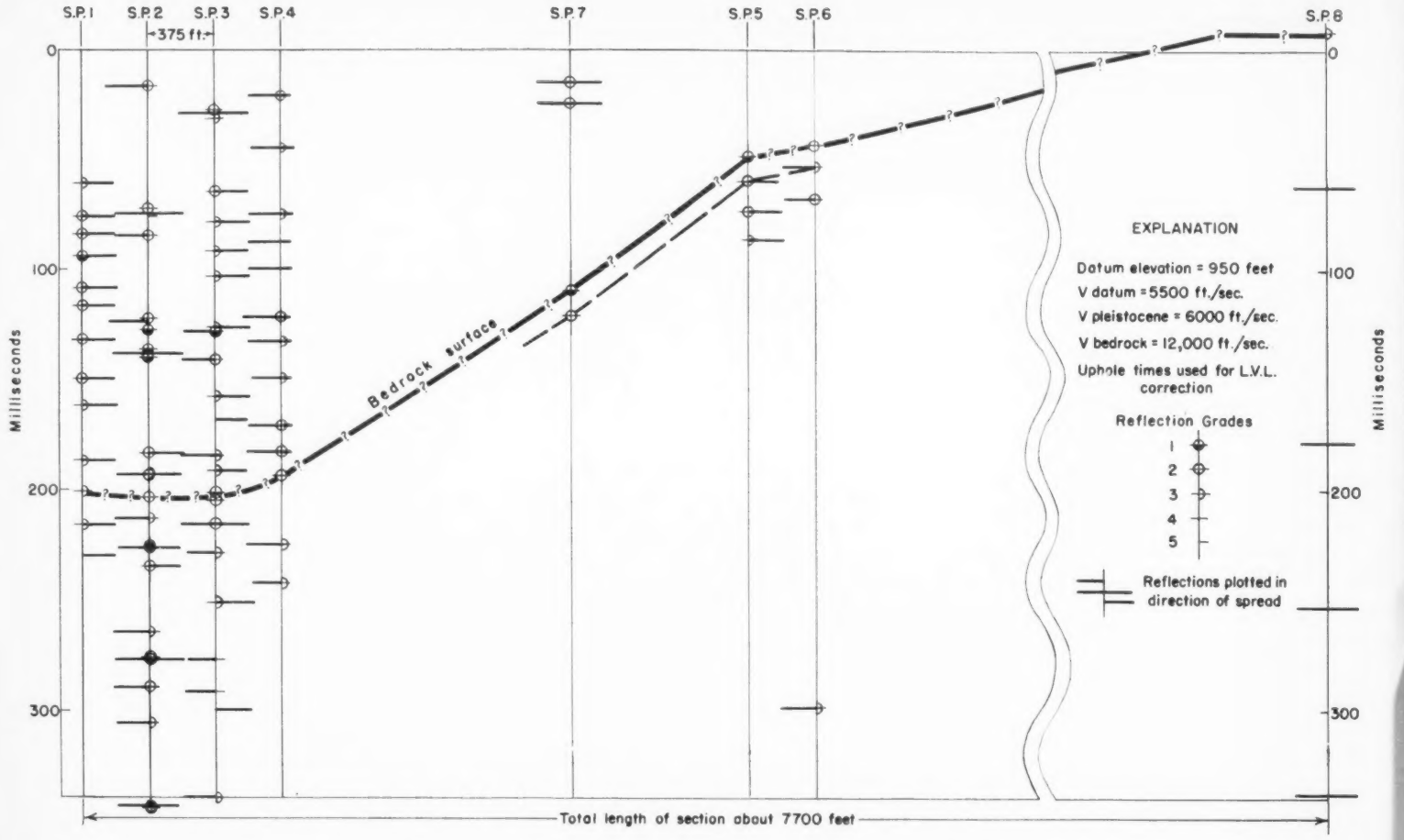

FIG. 9. Reflection time cross-section across buried valley, Portage County, Ohio.

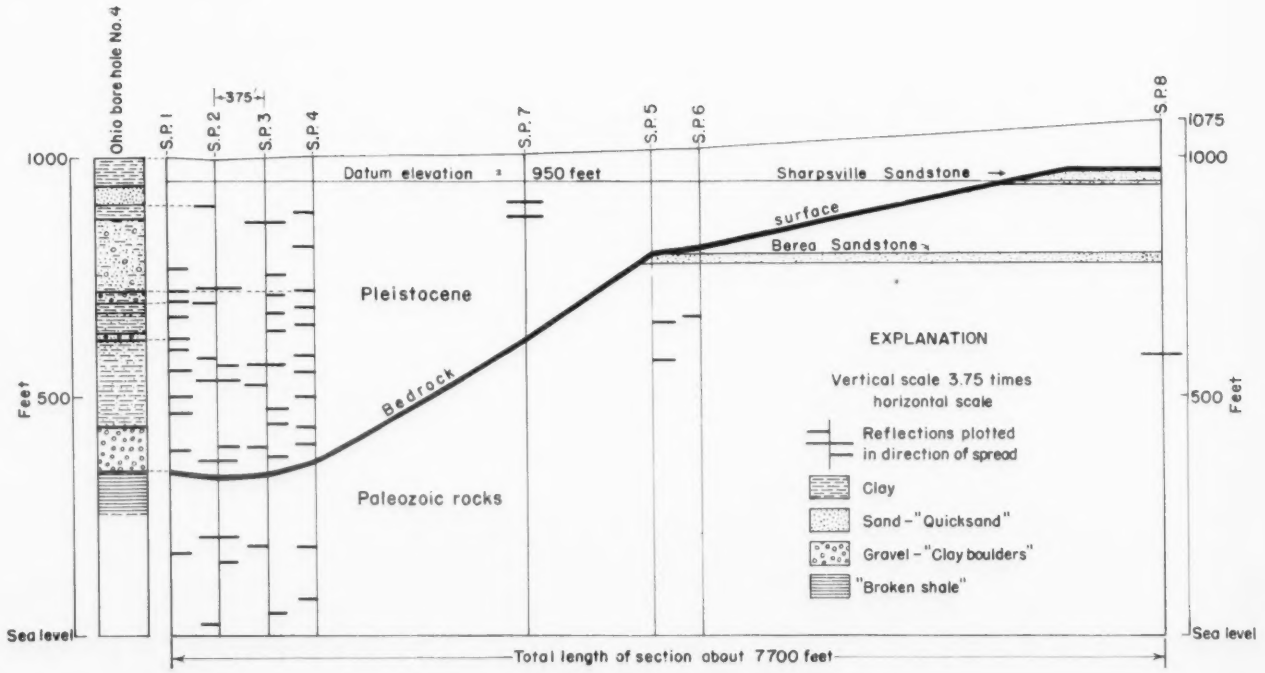

FIG. 10. Geologic cross-section across buried valley, Portage County, Ohio.

found in the bore hole. The depth to bedrock at the bore hole is 656 feet. The shallowest bedrock reflection along this line at Shot Point 8 comes from a depth of less than 100 feet. Several of the reflections from within the unconsolidated materials of Pleistocene age seem to correlate with clay beds. These reflecting horizons are not continuous and we would not expect them to be continuous, considering the manner of their deposition.

The prominent bench in the vicinity of Shot Points 5 and 6 was formed by the Berea sandstone, and the flat bench at Shot Point 8 was formed by the Sharpsville sandstone.

The shallow reflection seismograph seems to offer great promise in investigating ground water problems and other problems relating to bedrock topography, such as those found in Portage County, Ohio, and in studying Pleistocene geology.

CONCLUSIONS

The new, high-frequency seismic reflection systems have already found important uses in exploration for oil, both in mapping shallow horizons and deeper features where high resolving power is important. The shallow reflection seismograph also seems to offer promise in solving some of the problems of mining, engineering, and ground water investigations. Its use in these investigations will undoubtedly be severely limited for a number of reasons, but where there are favorable near surface conditions in areas where there are significant reflecting horizons at shallow to intermediate depths, the shallow seismic reflection method can be expected to yield more useful information than any other method, as the conventional seismic reflection method has done in oil exploration.

The near surface consolidated and unconsolidated sedimentary section which can be investigated by use of the shallow reflection seismograph can be thought of as approximating a 1/10 scale model of the deeper zones in which conventional reflection seismology is generally used. Viewed in this manner, the shallow reflection seismograph is subject to many of the same limitations as the conventional reflection seismograph and covers a similar range of possible uses. At the present stage of its development, the shallow seismic reflection method is conventional in everything but scale. Shallower, thinner, and more closely spaced horizons can be mapped, and smaller features can be located, but basically the method is a straight-forward extension of conventional reflection seismology.

Core drill and velocity control is of vital importance in shallow seismic reflection investigations.

In mining areas, the conditions favoring successful use of the shallow reflection seismograph may not often be found. Rugged topography, deep water tables (shots placed below the water table clearly favor good reflections), and highly heterogeneous near-surface materials are commonplace to the mining geologist and geophysicist, and these unfavorable conditions can be expected to restrict the use of the method. Favorable velocity contrasts and continuous reflecting horizons are less likely to occur in mining areas than in oil-producing areas. For many of

the really intricate problems in mining geology, still higher frequencies and some means of transmitting short-duration, non-explosive energy pulses into the ground must be perfected. Evison in New Zealand has already made considerable progress along this line (F. F. Evison, 1951*a*, 1951*b*, 1952, 1953, 1954).

With these limitations in mind, however, it is probable that the shallow reflection seismograph will become increasingly important in mining investigations where mineralization is stratigraphically or structurally controlled, or where a knowledge of the depth to bedrock is desired.

A variety of ground water problems involving depth to bedrock, shallow structure (artesian water), and, under certain circumstances, aquifers within unconsolidated materials may be solved with the help of the shallow reflection seismograph. Similar uses are suggested in engineering geology—for example, finding bedrock depths in permafrost areas where the high, near-surface permafrost velocity disqualifies the seismic refraction method. Shallow structures for the storage of natural gas near large cities may be found with the aid of the shallow reflection seismograph.

In addition, certain basic investigations of Pleistocene geology, modern glaciers and ice caps, and other near surface sediments may be advanced with the aid of the shallow reflection seismograph.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to D. R. Mabey, U. S. Geological Survey, who directed the field operations at Nokai Mesa and Deer Flat; to Allen F. Agnew and John D. Winslow, U. S. Geological Survey, with whose cooperation the work in Iowa and Wisconsin, and Ohio, was conducted and who supplied geologic information and guidance in these areas; and to L. C. Craig and other Survey geologists on the Colorado Plateau who encouraged and supported the experiments in that area.

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GEOPHYSICS, VOL. XXI, NO. 2 (APRIL, 1956), PP. 406–432, 12 FIGS.

GEOMAGNETIC MEASUREMENTS IN THE GULF OF MEXICO AND IN THE VICINITY OF CARYN PEAK*

EDWARD TITUS MILLER† AND MAURICE EWING†

ABSTRACT

Maps of the earth's total magnetic intensity at a 100-gamma contour interval are presented for most of the Gulf of Mexico and about 12,600 square miles surrounding Caryn Peak in the northwestern Atlantic. These were prepared mainly from data obtained during VEMA cruise No. 3 early in 1954. The field is remarkably uniform over an area including the deep basin of the Gulf of Mexico and extending northward almost to Texas and Louisiana. Numerous essentially circular anomalies of several hundred gammas amplitude exist near the edges of the calcareous West Florida and Campeche Banks. Caryn Peak exhibits a similar anomaly which is attributed to remanent magnetization of basic igneous rock. It is concluded that at Caryn Peak during the volcanic activity, probably in late Cretaceous time, the earth's magnetic field had approximately the same direction as now.

It is concluded that the scarps bounding the calcareous banks are not tectonic. It is suggested that they roughly coincide with lines of now buried basic volcanoes around which the limestone banks developed. In the area of the Gulf of Mexico which has been surveyed there is no anomaly like the several hundred gamma linear positive found off the eastern coast of North America, near the transition from a thick continental to a thin oceanic crust. If present, it must lie near the shoreline in the vicinity of Texas and Louisiana. This supports other evidence that the crust beneath the outer shelf and continental rise off Texas and Louisiana is of a thin oceanic type similar to that under the main basin. In this interpretation a thick column of sediments has spread out over part of the deep basin.

INTRODUCTION

During the VEMA cruise No. 3 in 1954 a marine magnetometer was towed for about 6,700 miles in the Gulf of Mexico and along the return track to New York. A survey was also made of a seamount known as Caryn Peak which is located about half way from New York to Bermuda. These measurements of the earth's total magnetic intensity along with other supplementary data have enabled us to prepare maps of total intensity at a contour interval of 100 gammas for most of the Gulf of Mexico and for a large area around Caryn Peak. From the variations in magnetic intensity geologic conclusions have been drawn.

MEASUREMENTS

The measurements of total intensity were made with a self-orienting flux-gate type magnetometer towed in a waterproof case 400 feet behind the vessel VEMA. The instrument is a modification of the AN/ASQ-3A M.A.D. equipment (Rumbaugh & Aldredge, 1949) which has been adapted for marine work (Heezen, et al., 1953). The instrument has been stabilized by employing a standard cell and a sensitive galvanometer in potentiometer circuits to detect small drifts in the total null current. Approximately every six hours, a measurement was made of the null current drift and the separation of the balance points for the instrument. The latter procedure yields a correction for variations in the electronic circuits

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which influence the instrument reading. The control box bridge circuit regulates the null current going to the detector coil. It has been tested so that any effect of non-uniformity of its scale can be removed from an instrument reading. The entire magnetometer has been calibrated with a Helmholtz coil both for relative and absolute sensitivity. The reported intensities have a probable instrumental error of 0.7 percent in absolute value, or about 350 gammas. The scale value for obtaining the difference between any two reported intensities is accurate to about 0.3 percent.

No corrections have been applied for diurnal or other time-variations of the earth's magnetic field. The peak-to-peak diurnal variation for quiet days in this area is about 25 to 50 gammas. Since the S_q varies considerably in time from the average S_q, introducing this statistically predicted average S_q as a correction is not justified. (Bartels et al., 1939a, 1939b; Vestine et al., 1947). The *K*-indices for all applicable three-hour intervals have been considered for San Juan, Tucson, and Cheltenham Observatories. This measure can be converted to maximum peak-to-peak irregular disturbance for the most disturbed element at the observatory. On only one occasion was significant disturbance noted. Correction on the basis of the actual disturbance recorded at either San Juan or Tucson would be unreliable since they are too far away to provide an effective base station. Furthermore it should be noted that the general amplitude of this disturbance was not sufficient to alter significantly the results as presented.

The final check on the consistency of the results is provided by comparison of observed values at 38 points in the Gulf of Mexico where two tracks intersect. The mean difference between pairs of readings is 39 gammas and only five exceed 75 gammas. This discrepancy results from errors in navigation, intensity measurement, and fluctuations of the earth's magnetic field.

This close agreement at intersections plus the regularity of the observed field over most of the area surveyed make it possible to use a 100-gamma contour interval even with rather widely spaced survey lines. The contours of equal total intensity for the Gulf of Mexico are shown in Figure 1 along with the position of the 100-fathom depth curve and the submarine scarps which partially surround the basin. The location of the 6,700 miles of marine magnetometer data and the 800 miles of airborne data reported by Affleck (1948) are indicated. These tracks are also shown on a generalized topographic map in Figure 2.

Adjustments were made to the observations to give exact agreement at every point where two tracks intersect. For VEMA tracks the mean of the two observation was accepted. The necessary correction to the observations was gradually reduced to zero along each track at a rate of about one gamma per mile. Affleck reported only anomalies, measured at an elevation of 8,500 feet. For use in Figure 1 these were restored to total intensity values on the basis of data supplied by Affleck. These results were then adjusted to agree with VEMA observations at seven intersections. The adjustment value had a mean deviation of only 50 gammas. As before, this discrepancy would result from navigation and measurement

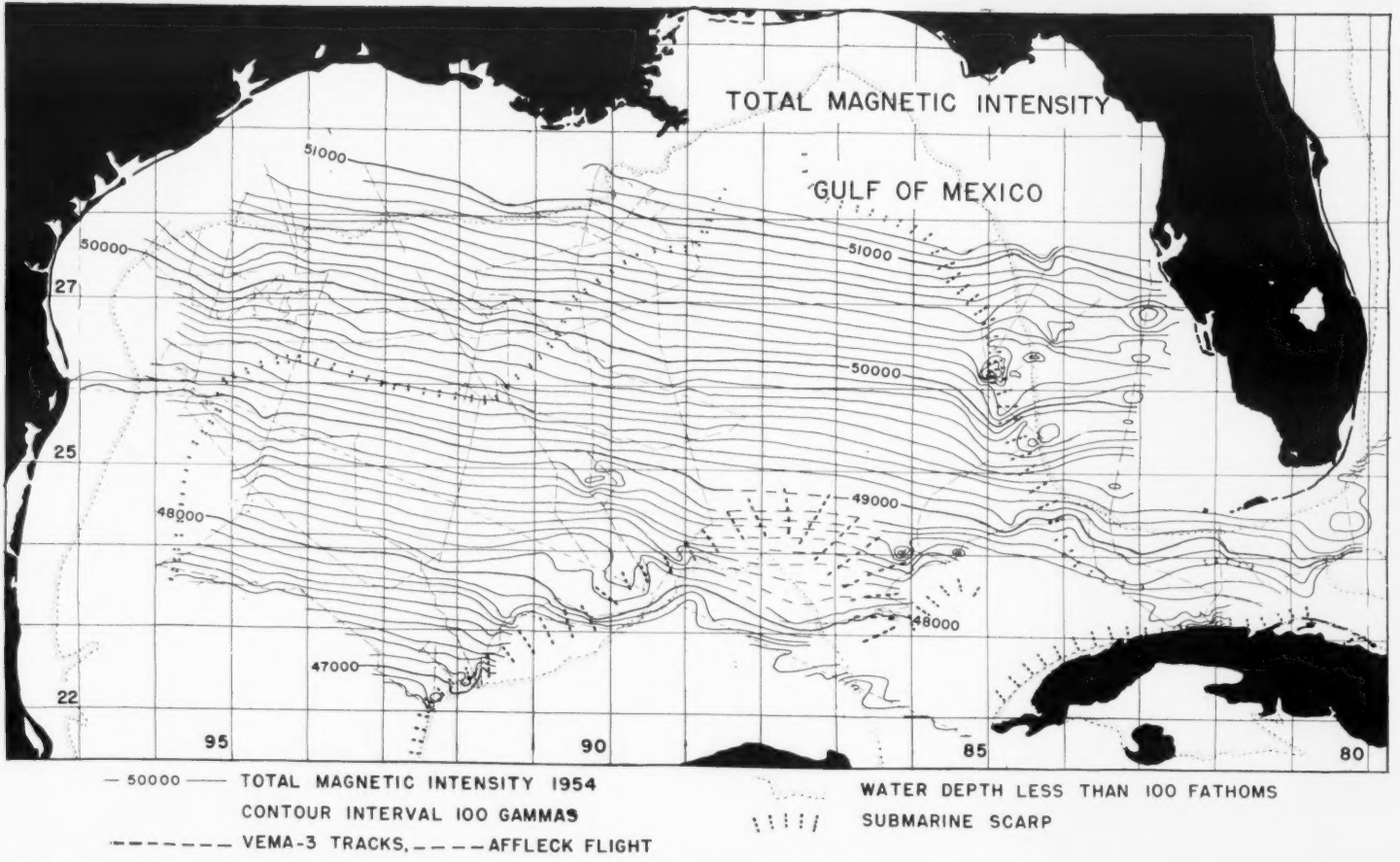


FIG. 1. Observed total magnetic intensity, 1954, over Gulf of Mexico with track lines indicated and the location of shelf areas and pronounced submarine scarps also shown.

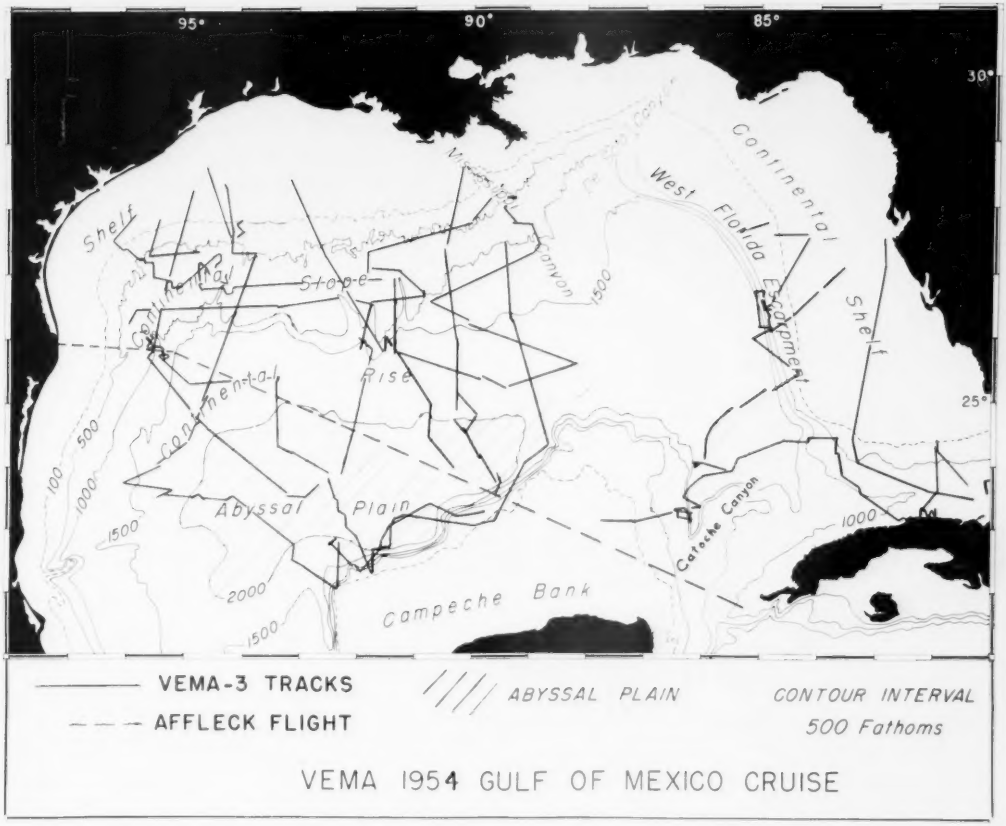


FIG. 2. A generalized bathymetric map of the Gulf of Mexico also showing the location of the magnetometer profiles.

errors, and fluctuations of the earth's field. The fact that these observations were made at 8,500 feet above sea level would also contribute to the discrepancy in anomalous areas. Affleck's values, thus adjusted, are properly comparable with sea level observations in the smooth part of the field. Elsewhere the actual anomalies at sea level are greater than those shown.

Figure 3 shows the total intensity contours for 1954 over the Gulf of Mexico calculated from publications of the Coast & Geodetic Survey and the Department of Terrestrial Magnetism (Deel & Howe, 1948; Vestine et al., 1948). The former were charts for the U. S. only, while the latter were for the world. The results of our survey are also presented on a 1,000-gamma contour interval. The regional field is represented by straight line contours at a constant separation chosen by

inspection to fit our data. The discrepancy between our 1,000-gamma contours and those taken from existing publications is somewhat larger than our uncertainty in calibration. Instrumental improvements now being made will allow the latter uncertainty to be reduced to about 40 gammas. The subject of absolute values over broad regions will be treated in a separate paper.

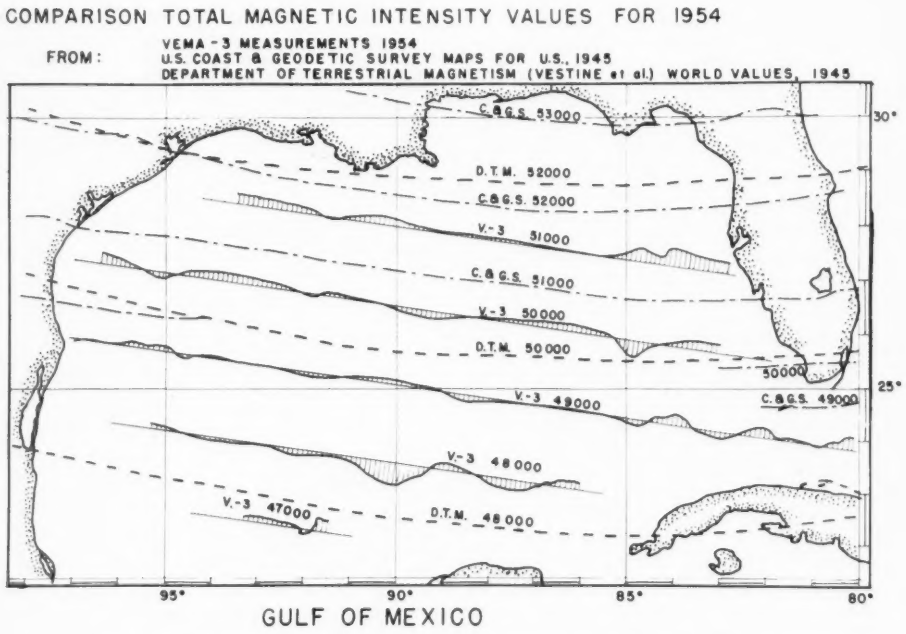


FIG. 3. A comparison of the region of total magnetic intensity as derived from VEMA-3 measurements, U. S. Coast and Geodetic Survey maps for the U. S., and from the Department of Terrestrial Magnetism world wide magnetic values.

During the return leg of VEMA-3 cruise Caryn Peak, an isolated seamount half way from New York to Bermuda, was surveyed with the magnetometer for the specific purpose of allowing comparisons between its anomaly and those seen in the Gulf of Mexico. Data from other cruises have been incorporated to allow a 100-gamma contour interval map to be prepared for about 12,600 square miles surrounding Caryn Peak. This map is shown in Figure 4, along with the control and the outline of Caryn Peak. The seamount is essentially a simple cone which is about 6.5 miles (12.0 km) wide at the base on a flat sea floor 2.6 miles (4.8 km) deep and which rises to about a mile wide summit with a depth of 1.7 miles (3.1 km) (Tolstoy, 1951).

GENERAL DISCUSSION OF THE RESULTS

It is seen from Figure 1 that the magnetic field is remarkably uniform over the greater part of the area surveyed. This area corresponds generally to the abyssal plain and continental rise which together form the nearly flat floor of the main basin of the Gulf of Mexico. These depths range from 1,500 to 2,000 fm (Ewing et al., 1955).

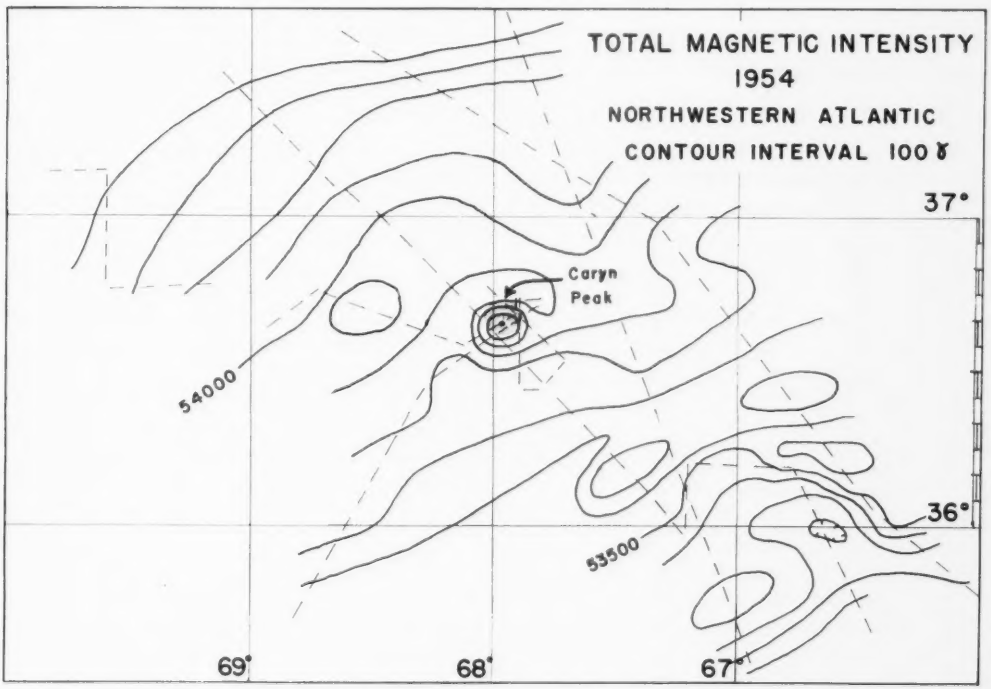


FIG. 4. Observed total magnetic intensity, 1954, over the Northwestern Atlantic with the outline of the base of Caryn Peak indicated. Declination 14° W. (Vestine et al. 1948).

In marked contrast, the magnetic field over the Campeche Bank and the West Florida Bank has numerous strong anomalies. Although a further survey is needed in these areas, it is apparent that the anomalies are not linear but are 5 to 20 miles in diameter, and up to 400 gammas in amplitude.

The boundary between the two types of field is sharp and generally coincides with the steep scarp separating the two flat limestone platforms (Eardly, 1951) from the deep basin. The coverage in the vicinity of the Campeche and West

Florida Scarps is sufficient to show definitely the absence of a linear anomaly which would be associated with a large normal fault in the basement rock.

Figure 5 shows an interpretation of seismic refraction results (Ewing et al., 1955). About 7 km of sediment is in the main basin, with not more than 5 km of crustal rocks between it and the Mohorovičić discontinuity. Velocities found for the upper mantle are 8.0 to 8.3 km/sec, with 6.2 to 7.1 km/sec for crustal rocks. Several layers of sediment were identified with velocities ranging from 1.5 to 5.2 km/sec.

One profile on Campeche Bank gave only slight penetration indicating a velocity of about 5.7 km/sec at 2 km depth which might be either dolomite, limestone, or crystalline basement. Core samples from the scarp yield limestone and dolomite, often as angular fragments.

The northern boundary of the deep basin is also a scarp. Its height above the floor is less than that of the other, and numerous sediment cores show only unconsolidated clastics. The uniform magnetic field continues from the basin across this scarp to the limits of the area surveyed.

A positive anomaly, of several hundred gammas amplitude, has been observed numerous times at the edge of the continental shelf along eastern North America (unpublished Lamont Observatory and U.S.G.S. data and as reported by Keller *et al.* (1954) for two flights to Bermuda). A similar anomaly is not present in the part of the Gulf of Mexico surveyed by the VEMA. A small aerial survey flown by the U.S.G.S. near the coast of East Texas and Louisiana suggests that a linear anomaly of about 100 gammas amplitude may be present (Balsley, 1949). Further data are required to determine whether this feature is comparable with that found off the east coast of the U. S., where refraction seismology has shown the crust to change from thick continental type to thin oceanic type (Ewing, et al., 1950; Officer and Ewing, 1954).

In any case the absence of this anomaly over the shelf far from shore supports the conclusion suggested in Figure 5 (from Ewing et al., 1955), namely that much of the shelf off Texas and Louisiana is a thick sedimentary layer built up over a crust of the same type as found in the center of the basin and that the typically thick continental type crust does not appear until near the shoreline. Other evidence for the oceanic nature of the crust under the Gulf of Mexico comes from the L_g observations (Press and Ewing, 1952). They show a limit for L_g propagation, based on Palisades recordings of Mexican and Central American earthquakes, in the neighborhood of a line through 26° N.–97° W. and 30° N.–92.5° W. Worzel and Shurbet (1955a, 1955b), from their analysis of gravity anomalies, have reached the conclusion that in this region much of the continental shelf consists of a thick column of sediments over a thin oceanic type crust.

The aseismic nature of the area including the youthful Sigsbee Scarp has been pointed out by Ewing and Heezen (1956) as strong evidence that the origin of this scarp is limited to processes in unconsolidated sediments and not controlled by

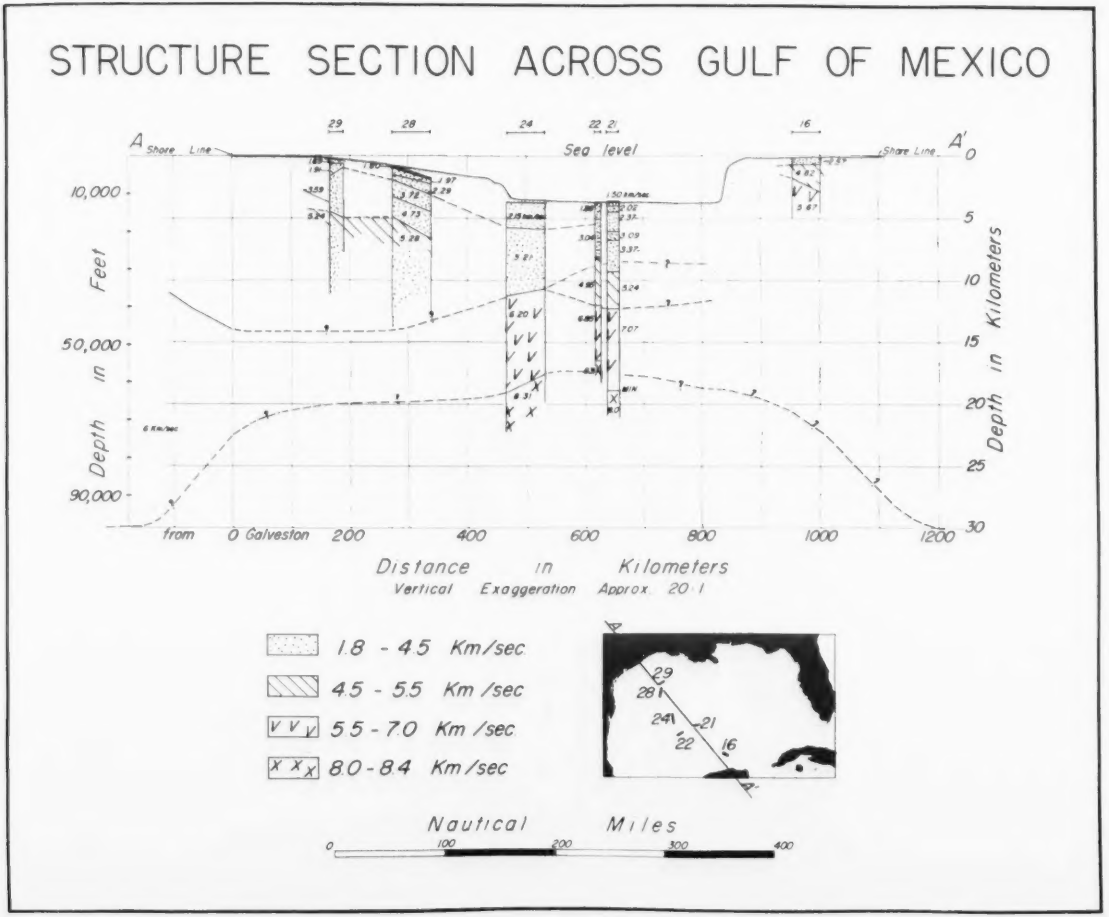


FIG. 5. Composite seismic structure section along profiles on a line crossing the Gulf of Mexico from Galveston to Yucatan Peninsula (Ewing et al., 1955*a*).

tectonic activity in the basement. The smooth magnetic field over the rough topography of the continental slope and Sigsbee Scarp supports this conclusion.

The remarkably uniform magnetic field found over large areas such as the Gulf of Mexico Basin is not fully explained. There is a similar region off the Atlantic coast of North America from Newfoundland to the Bahamas, which is the subject of a paper now in preparation. Two examples for this area are given by Keller (1954). Two cracks cross undisturbed areas near the coast of Africa (Heezen et al., 1953). Areas of "nonmagnetic" basement in continents have been mentioned by others occasionally, but the writers have not seen data on the areal extent of these features. Delineation of such areas can be done rapidly since widely spaced traverses can define the magnetic field within them. Explanation of their cause may give an important clue to other processes which occur at continental margins.

In Figure 6 these features are demonstrated by presenting the observed anomaly and bathymetric profiles for five lines across the Gulf of Mexico. The anomaly was computed using a linear regional field derived by inspection as illustrated in Figure 3. Profiles I, II, and III are across the western half. They show that at places Campeche Scarp can be crossed without any anomaly. Figure 1 adequately demonstrates that large anomalies are present at other points on the scarp. The lack of any correlation between the rugged continental slope off Texas and Louisiana and the magnetic field is also clearly shown.

Most of profiles IV and V are over or near the calcareous Campeche and West Florida Banks. Profile IV has several course changes which keep the point of observation in deep water but in the vicinity of a scarp. Between points *s* and *t*, this track crosses the basin between Campeche and Florida and the magnetic field is found to be uniform.

The large local anomalies which are generally observed near the edge of the Campeche Bank and the West Florida Shelf could result from basic volcanic cones now buried by as much as two miles of calcareous sediments. From unpublished results of G. P. Woollard based on data of the U. S. Bureau of Mines (Lee et al., 1945), it seems likely that the magnetic field in the southern half of Florida is of the same character, but more information would be required to establish this point. In any case the essential fact is that magnetic anomaly centers exist under the Campeche Bank and West Florida Shelf. Simple calculations show that they would still be observable in measurements made at 10 km elevation. Consequently the fact that they are not observed over the main basin of the Gulf of Mexico must mean that the basement there is different. It is more homogeneous and generally lacks these anomaly centers.

Magnetic measurements made over Caryn Peak, an isolated volcanic cone, are presented in Figure 4. The variations in total magnetic intensity associated with this seamount are comparable, in amplitude and width, with those seen over the Campeche Bank and West Florida Shelf. Calculations for the anomaly to be expected from an isolated seamount of the general size of Caryn Peak show that its rock has a magnetization of about 0.006 cgs. This high value definitely implies

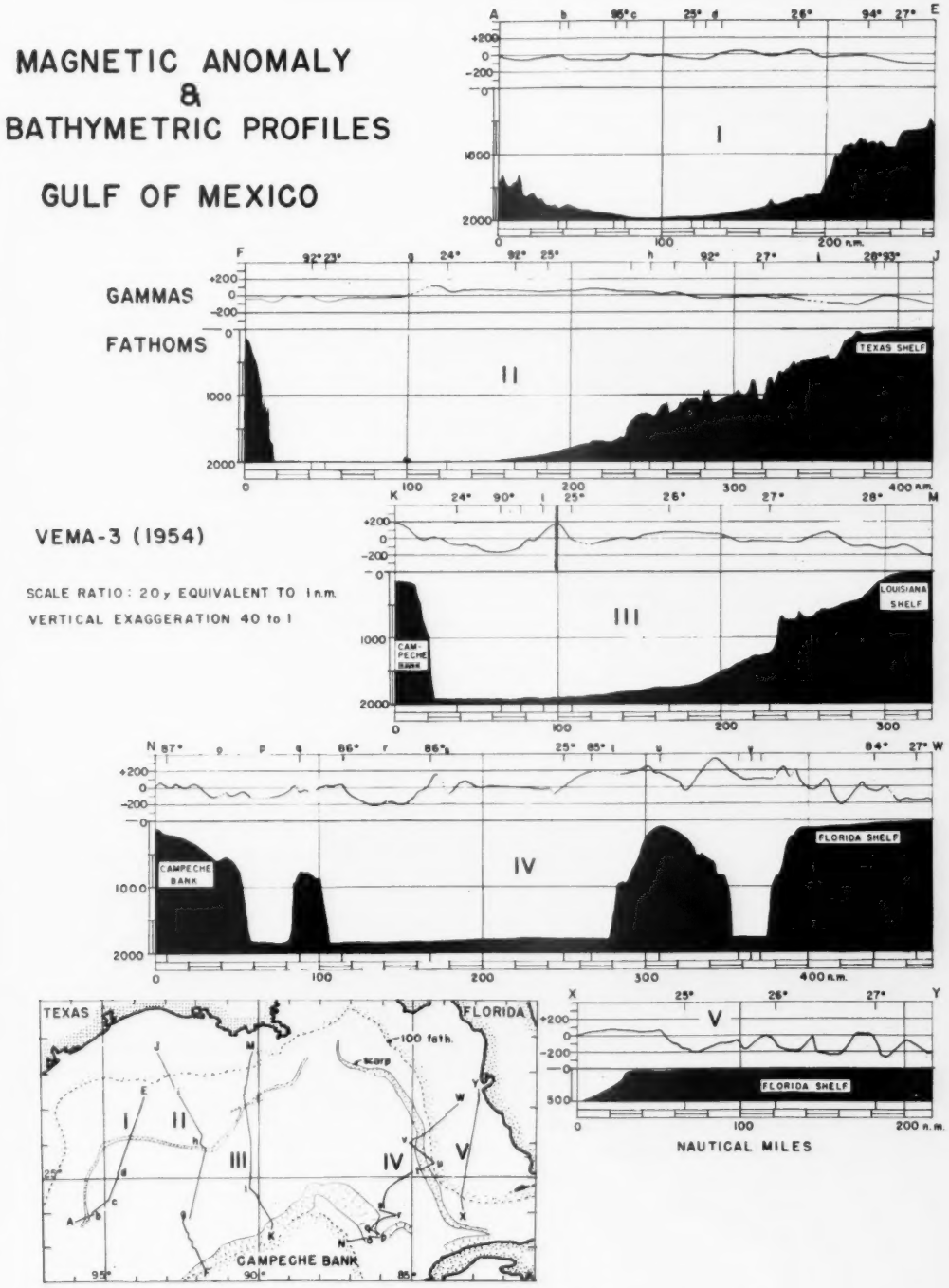


FIG. 6. Profiles across the Gulf of Mexico showing total intensity anomaly and simultaneously observed water depth.

that the mountain is mainly basic rock with an appreciable effective natural remanant magnetization. Core A158–3, depth 3,790 meters (2,070 fathoms), on Caryn Peak showed 1.32 meters of altered basic volcanic rock (D. Ericson, personal communication). Other implications of these magnetic measurements at Caryn Peak will be discussed later. It is suggested that the anomaly at Caryn Peak may be considered as the prototype of the anomalies found at the edges of the Campeche and West Florida Platforms.

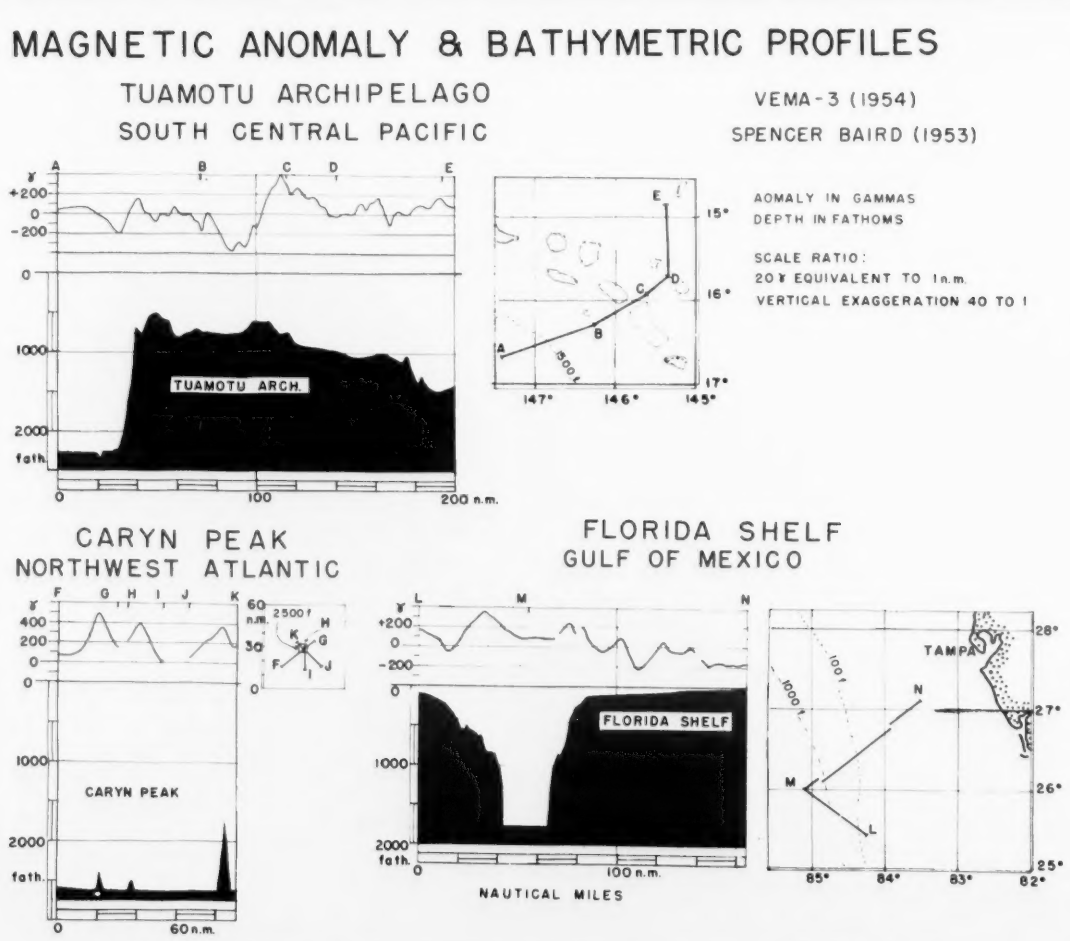
The island of Bermuda, with very steep submarine slopes, is a calcareous platform which rests on a basic volcanic cone. Surface geology, a deep well, and seismic, gravity and magnetic surveys demonstrate this (Pirsson and Vaughn, 1913, Officer et al., 1952., Woollard, 1954, and Keller et al., 1954). Thus Bermuda with its sides as steep as those of the West Florida and Campeche Banks is considered as an example showing a stage in the development of these banks.

If these edges of the West Florida and Campeche Banks are formed on a row of basaltic volcanoes which subsided as lime formed, we could account for the observed anomalies, the scarp-like character of the edge and the general character of the carbonate sediments. Although only limited magnetic data from a recent VEMA cruise are available for discussing the Bahama area, similarities in these data and in the topography and geologic column suggest a similar pattern for the eastern edge of the Bahamas. According to this view, the eastern front of the Bahamas Islands, especially from Cat Island to Navidad Bank, resembles the West Florida and Campeche banks at an early stage in their development. This is in accord with conclusions of Lee (1951), who interpreted gravity observations and other data for the vicinity of Abaco, Eleuthera, and Ragged Islands in the Bahamas.

In Figure 7 three groups of simultaneous bathymetric and magnetic profiles are presented for comparison. One is an anomaly found over the Florida Shelf. The second is the observed magnetic intensity on three crossings of Caryn Peak. The third is a crossing of Tuamotu Archipelago in the South Central Pacific (Mason and Miller, manuscript in preparation). This archipelago consists of calcareous atolls which stretch over 1,000 miles in a NW.-SE. direction across the Pacific (Marshall, 1911; Chubb, 1934). The platform on which they sit is bounded by very steep submarine slopes. As shown in the profile the platform depth along the SW. side of the archipelago is between 500 and 1,000 fathoms.

It can be seen immediately in Figure 7 that two crossings of the West Florida scarp about 20 miles apart show dissimilar anomalies. This again demonstrates that we are dealing with a series of distinct anomalies rather than one continuous feature. The general amplitude and width of these anomalies are of the same order as seen over Caryn Peak. Likewise the fundamental anomalies over the Tuamotu Archipelago are of the same general size and extent.

Superposed on these Tuamotu anomalies are smaller and shorter ones which could have a number of causes. However, we note a similarity with the magnetic field over the Bermuda Platform in the Atlantic as reported by Keller (1954) and



[FIG. 7. Profiles showing total intensity and simultaneously observed water depth on the same scale for comparison between the West Florida Shelf, Caryn Peak, and Tuamotu Archipelago.

also as seen in unpublished VEMA observations. At Bermuda the fundamental anomalies are large features which would be expected from large basaltic mountains with strong remanent magnetization. The additional smaller anomalies can be explained as secondary volcanism where smaller bodies of rock have cooled in place and acquired remanent magnetization. They may be surrounded by ash, breccia, or sedimentary rocks with smaller effective magnetization. The net effect of thermal remanent magnetization in igneous rocks which have cooled through the Curie-point while in place usually exceeds magnetization induced by the present field after the rock has cooled (Nagata, 1953). Thus the remanent moment usually causes the large anomalies. An example of this effect can be seen at Mt. Moffet on Adak Island, Alaska, which has two cones: one predominantly olivine-basalt, the other tuff-breccia. The one large anomaly can be explained by thermal remanent magnetization of the olivine-basalt cone in the present direction of the earth's field (Vacquier et al., 1951; Keller et al., 1954).

DISCUSSION OF SPECIAL FEATURES IN GULF OF MEXICO

In Figure 2 the Catoche Canyon (Ewing and Heezen, 1956) makes a conspicuous indentation into the scarp on the northeast side of the Campeche Bank. Figure 1 shows that a considerable part of the canyon is without magnetic anomaly, while to the north a large, essentially circular anomaly is seen. Faulting of the order of the height of the canyon walls would produce an observable anomaly unless the up-thrown surface of the basement rock was at a depth far greater than the canyon floor. We conclude that the canyon itself is not of tectonic origin. Similar canyons in the Bahamas have been investigated with gravity measurements and found to be non-tectonic (Worzel et al., 1953 and 1955a). It appears that these canyons must be explained by processes in the growth of calcareous banks and not by secondary tectonic action. Newell (1953) has reached similar conclusions from geological studies of the Bahamas.

In Figure 6, Profile II at point *g* the bathymetric profile shows 70 fathoms relief. This is a crossing of Sigsbee Knolls, a group of three hills within 15 miles of each other and individually less than 6 miles across. They rise about 100 fathoms above the surrounding abyssal plain. Two cores taken on the knolls show sediments entirely free from turbidity current deposits, while cores from the plain show abundant evidence of such deposits (Ewing et al., 1955 and 1956).

While the profile II reveals a small broad anomaly slightly north of the Knolls, inspection of the map, Figure 1, at 24° N. and 92° to 93° W., will show that this is caused by a broad meander of the contours of magnetic intensity which covers too large an area to be associated directly with these small knolls. None of the numerous short traverses directly across the Knolls revealed an anomaly.

If the Knolls were minor igneous masses lying on top of the abyssal plain, then depending on their magnetization they might produce too small an anomaly to be detected. However, if they were summits of buried igneous mountains of appreciable size they would definitely be observable. Since the former seems quite

unlikely, Sigsbee Knolls are judged to be a structure in which volcanism plays little or no part.

In Profile III, Figure 6, at point e we see the one significant anomaly found in the map of magnetic intensity for the entire deep basin. This is similar to those which have been associated with basic volcanic peaks at considerable depth. There is no topographic expression of this anomaly. No other such anomaly was found, hence they must be rare.

COMPARISON WITH CONTINENTAL MEASUREMENTS

Comparison can be made between the magnetic field found over the Gulf of Mexico and over the Illinois Basin, a typical continental sedimentary basin. In Figure 8 profiles have been plotted for tracks across Indiana and Illinois on the basis of measurements made by the U.S.G.S. and Aero Service Corp. (Mead et al., 1949; Jensen, 1949). In this area the depth to pre-Cambrian basement is said to vary from 3,000 to 12,000 feet, being greatest in the southwest corner. A profile across the West Florida Shelf is shown on the same scale for comparison.

Except under special conditions, the direct interpretation of magnetic anomalies is difficult. However, it is to be noted that the areal extent and amplitude of the major anomalies observed in Indiana and Illinois are greater than those found over the West Florida Shelf. Furthermore, as would be expected, even where basement depth is 12,000 feet, the field is not uniform as it is over the Gulf of Mexico Basin. The crust beneath the Illinois Basin differs in its magnetic properties from that beneath the Gulf of Mexico and its adjacent shelves.

DISCUSSION OF CARYN PEAK

Caryn Peak is an isolated volcanic seamount which has a simple topographic form. The magnetic field as contoured in Figure 4 lacks perfect bilateral symmetry. With the control as shown in Figure 4 it would be possible to close the 53,900 gamma contour east of the seamount, making the contours near the seamount more symmetrical. The anomaly presented in Figure 9 has a 350 gamma maximum about 2.5 miles south of the summit. It was obtained by removing the regional field with contours which trend N. 67° and have a gradient of 8.3 gammas per mile and also a broad positive anomaly centered at 36° 45′ N. and 67° 30′ W. which is indicated by the southward bulge of the contours in this region.

Since the anomaly from a uniformly magnetized sphere can be directly calculated using the formula for a simple dipole, it is useful to consider spheres in calculating the approximate total intensity anomaly for a given body. Taking two spheres, one resting inside the other, with equal and opposite magnetization the anomaly for a spherical cap having a volume similar to that of a conical seamount may be found (see Figure 10). Two such spheres with radius of 2.50 and 2.20 miles whose centers are at depths of 4.20 and 4.50 miles respectively produce a maximum total intensity anomaly of 350 gammas when their magnetization is .0049 cgs. implying a susceptibility of .009 cgs. The anomaly peak is

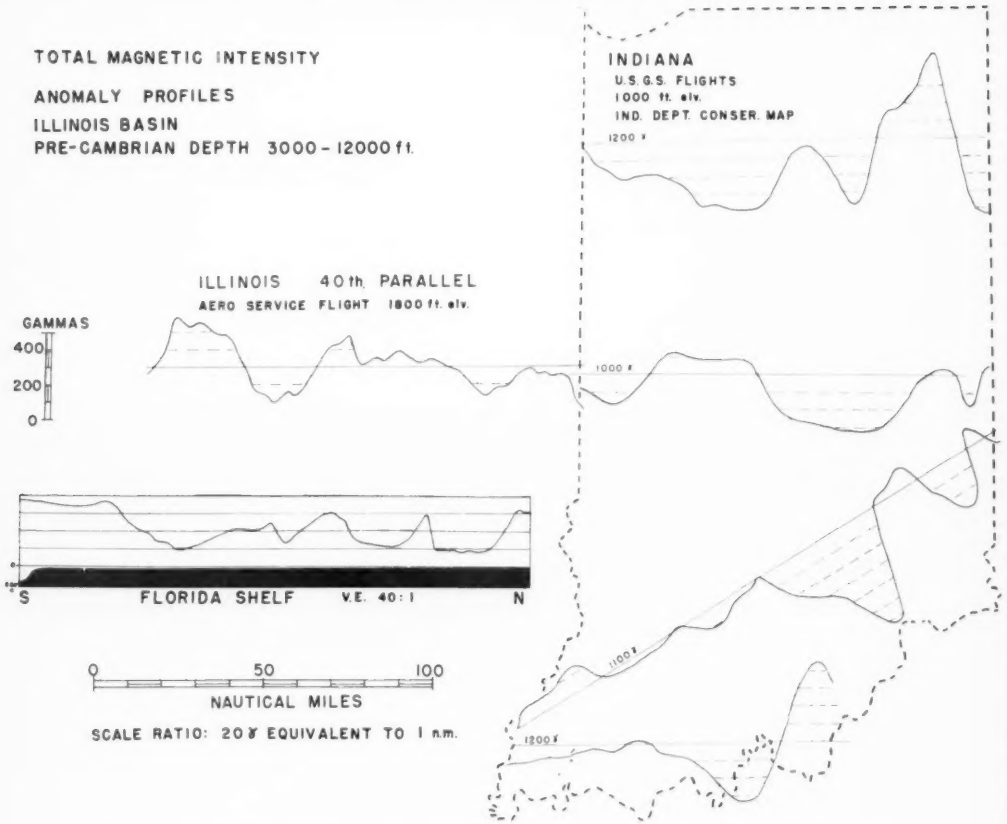


FIG. 8. Total magnetic intensity profiles plotted along lines across Indiana and Illinois with a track across the West Florida shelf for comparison.

0.7 miles south of their centers. The net volume of magnetized matter in this case is 1.6 times that of a simple cone 7.0 miles in diameter and 1 mile high. Reducing the net volume in the spherical cap would make the required magnetization increase.

A method for computing the total intensity anomaly for an arbitrary three-dimensional body is developed in the appendix. Using this method we have computed the anomaly for a truncated pyramid with a square base 6.2 miles wide and 0.9 miles high which is magnetized in the direction of the main field. The value $69\frac{1}{4}°$ for inclination was obtained from the D.T.M. worldwide values (Vestine et al., 1948). We find that a magnetization of .0058 cgs. or a susceptibility of .0107 cgs, will produce a maximum anomaly of 350 gammas located about 1 mile

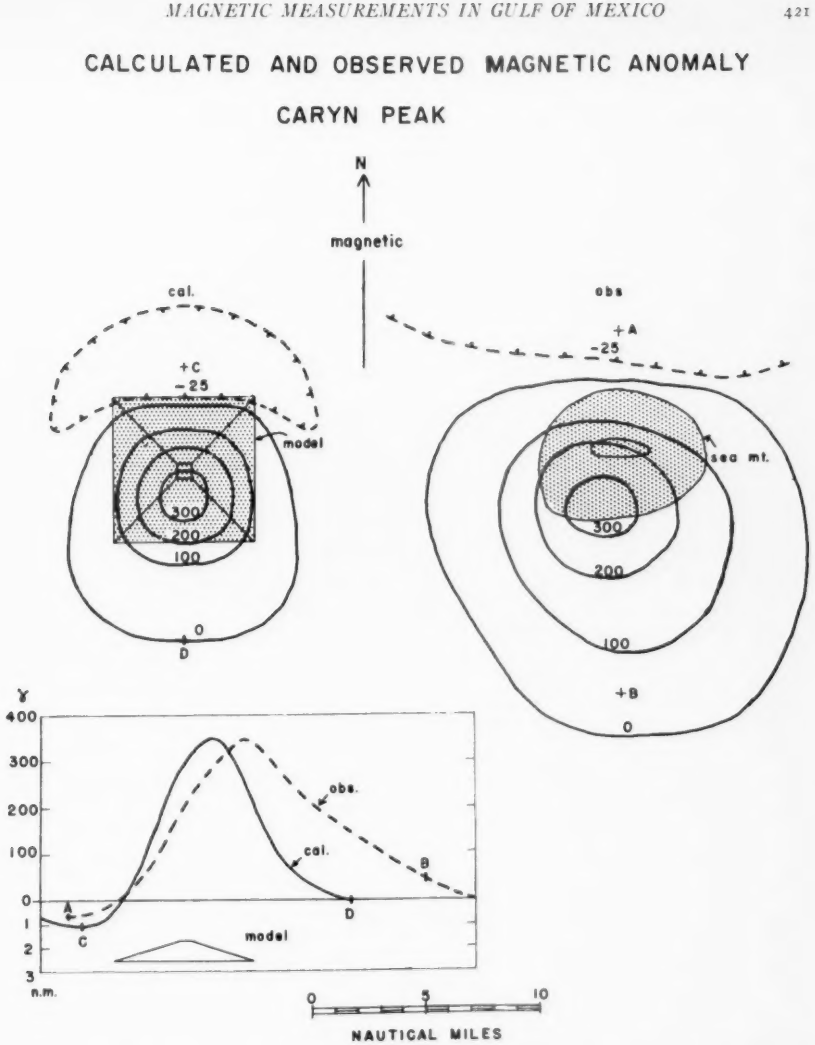


FIG. 9. Calculated and observed magnetic anomaly over Caryn Peak with the shape and location of the seamount and the model indicated.

south of the summit. These results for the truncated pyramid are present in Figure 9.

The observed anomaly covers a larger area than the calculated anomaly, and its maximum is displaced farther south of the summit. The discrepancies may

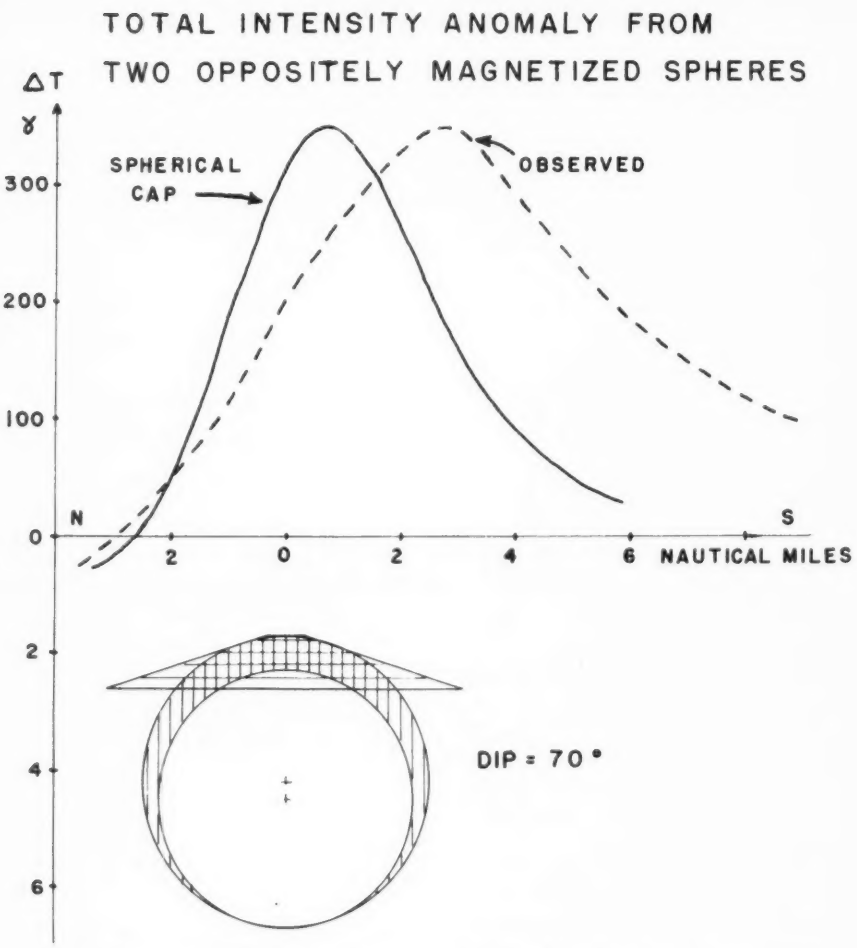


FIG. 10. The total intensity anomaly along a N.-S. profile over a model where magnetic material occupies the volume between two spheres of 2.5 and 2.2 miles radius, the latter resting inside the former.

arise from extension of the cone downward below the ocean floor, or from omission of the effect of the volcanic neck.

The effect of the neck will be negligible unless its cross section is an appreciable fraction of that of the base of the cone or its intensity of magnetization greatly exceeds the mean for the seamount. The downward extension of the seamount is presumably limited to about two-thirds of a mile by the thickness of the sedi-

mentary layer (Ewing et al., 1954). Moderate downward extension would broaden the anomaly pattern but could not increase appreciably the asymmetry unless the buried portion is strongly asymmetrical.

In order to explain the discrepancy between the calculated and the observed width of the anomaly and also the location of its maximum, various cases have been studied. If the direction of magnetization dips less than the main field the anomaly is attenuated but not appreciably extended southward. If a large diameter spherical cap is selected to produce an anomaly which fits the observed curve it will still require magnetization of about .004 cgs, even though the material with net magnetization is seven times the volume of Caryn Peak and a volume about that of Caryn Peak is above the sea floor. Furthermore the calculated maximum is still not located as far south of the summit. However, skewing the spherical cap so that more magnetic material lies on the south side improves the location of the calculated maximum anomaly.

A study of the residual anomaly, found by taking the difference between the observed anomaly and that calculated for a truncated pyramid at various amplitudes of magnetization, shows that if the residual is caused by a slab less than two-thirds of a mile thick lying beneath the sea floor, then the magnetization required for both the pyramid and the slab is approximately .005 cgs. The bulk of the slab must be located on the south side of the summit.

These studies have shown that an appreciable amount of magnetic material must be below the sea floor with the greatest amount towards the south. However, as long as two-thirds of a mile is taken as a limit for the thickness of this buried material, the magnetization must be about .004 or greater. The essential fact is that without any doubt Caryn Seamount is magnetized approximately in the direction of the present earth's magnetic field. Furthermore the intensity of magnetization is probably greater than allowed by accepted values of susceptibility for basic effusive rock.

Slichter reported susceptibility data grouped into the following igneous rock types: basic effusives, basic plutonics, and granites and allied rocks (Birch et al., 1942). In each case more than 50 samples are considered. Granites have a frequency maximum for susceptibilities less than 10^{-4} cgs. Basic rocks have the frequency maximum for susceptibilities about 10^{-3} to 4×10^{-3} cgs. However, the basic effusives had a sharp frequency peak which would indicate susceptibilities should not be expected much above 4×10^{-3} cgs.

Nagata (1953) gives susceptibility data for a large number of rock samples. Only basic rocks show a significant number of samples with values greater than 10^{-3} cgs. Only one sample listed by Nagata has a value as large as .011 cgs. Considering only specimens within a factor of ten of the required amount, we find that only six of the 79 samples had susceptibilities which were greater than one-half of the required amount. Thus the magnetization at Caryn Peak is probably too large by a factor of at least two to be isothermally induced.

Königsberger introduced the term Q_n giving the ratio of natural remanent

magnetization to induced magnetization. Nagata has introduced the term Q_t for the ratio of experimentally induced thermal remanent magnetization to isothermal induced magnetization and has shown that large natural remanent magnetization must be a thermal remanent effect produced when the rock cooled through the Curie point (Nagata, 1953; Bruckshaw, 1954). The essential fact is that Q_t is about equal or somewhat greater than Q_n, and that they generally lie in the range of values from two to ten for normal igneous rocks and sometimes even reach values as high as 100. Thus thermal remanent magnetization of basic rock will provide a magnetization large enough to account for the anomaly at Caryn Peak. In other words, this magnetic anomaly probably records the earth's field which existed when the lavas cooled through the Curie point.

From unpublished data on the submarine cores which have been interpreted by D. Ericson at Lamont Observatory, the following facts are derived. Upper Cretaceous fossils have been altered by replacement or re-crystallization of the original $CaCO_3$ in a manner which can only be due to volcanism. Later forms, with various Tertiary ages, which are capable of easy alteration, are unaffected. Assemblages have been found thoroughly mixed as if by slumping. Miocene forms are present. In one case there is a fossil which is probably confined to the Eocene, while another one is supposed to be restricted to the Paleocene. It has been concluded that the evidence strongly suggests volcanism took place towards the end of Upper Cretaceous time.

These facts are of immediate significance to theories about the history of the earth's magnetic field, particularly to those which postulate numerous reversals (Runcorn, 1954), and to those on polar wandering inferred from paleomagnetism (Hospers, 1954). The implication of the present study is that the magnetic field direction was essentially the same throughout the volcanic development of Caryn Peak in the Upper Cretaceous time as it is now. Assumption that the observed anomaly is isothermally induced by the present field requires an improbably high susceptibility. Assumption of a series of reversals of the earth's field during the building of Caryn Peak, like those inferred from the Iceland basalts by Hospers (1954), would imply cancellations of anomalies produced by remanent magnetism, and again require improbably high susceptibility.

To date there are insufficient results available on anomalies over oceanic islands and seamounts to permit definitive conclusions. However, the present study indicates that thermal remanent magnetization may be responsible for a large part of the anomaly over a seamount. Consequently further study of the anomalies over selected seamounts and islands along with coring and dredging, in an effort to date the volcanism and collect representative igneous rock, should produce definitive results bearing on the question of repeated reversals of the earth's field. Unless weak or reversed polarization for some seamounts is found, one must choose between accepting a very high value of susceptibility or abandoning the hypothesis of numerous reversals of the main field.

CONCLUSION

The use of the marine magnetometer on the vessel VEMA has allowed us to prepare maps of total magnetic intensity for the Gulf of Mexico and a large area around Caryn Peak in the northwestern Atlantic. From these measurements, we conclude that the deep basin of the Gulf of Mexico and the outer shelf north of the basin adjacent to Texas and Louisiana is underlain by a crust with homogeneous magnetic properties similar to that found beyond the continental shelf off eastern North America.

The West Florida Bank and Campeche Bank are quite different from these uniform areas. Large anomalies seen near the edges of these limestone banks could be produced by now buried basic volcanic mountains. They would have provided the sites from which the calcareous banks could have grown. Caryn Peak is considered a prototype of the volcanic cone, and Bermuda as an example of the evolution of a volcano into a calcareous platform with sides as steep as those of the West Florida and Campeche Platforms. The steep submarine scarps which bound these banks must be non-tectonic features. In crossing this boundary the magnetic field changes from being characteristically smooth to being rather irregular.

Caryn Peak has an anomaly concordant with magnetization essentially in the direction of the present field. However, the degree of magnetization strongly suggests that it is thermal remanent magnetization of basic rock acquired during volcanism tentatively dated as late Cretaceous. This affects theories about the history of the earth's main magnetic field. Surveys of a sufficient number of seamounts may permit a conclusion about the fundamental question whether natural reversals of the main field took place frequently during geologic time.

No large linear positive anomaly like that at the edge of the continental shelf along eastern North America was found in the Gulf of Mexico. Scanty evidence suggests that it may lie near the shoreline of Texas and Louisiana. This supports the view that the shelf there consists of a thick column of sediments overlying a thin crustal column essentially the same as found seismically under the deep basin.

The explanation for the unusual uniformness of the magnetic field often observed over extensive deep oceanic areas which surround continental areas has not yet been given. More field work is necessary to establish the essential facts. Additional marine magnetic measurements can give valuable information about crustal rock in this area where the transition from continental to oceanic type occurs.

ACKNOWLEDGMENTS

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APPENDIX

Method for Calculating the Total Intensity Anomaly for Buried Magnetic Body

The total intensity anomaly ΔT can be written in terms of the northward horizontal anomaly , ΔF_x, the vertical anomaly, ΔF_z, and the angle of dip of the main field, D, as follows:

$$\Delta T = \Delta F_x \cos D + \Delta F_z \sin D. \tag{1}$$

If the buried body has a uniform magnetization with a moment per unit volume of $\vec{M} = M_x\vec{J}_x + M_z\vec{J}_z$, the anomaly components can be written as surface integrals over the body.

$$\begin{aligned} \Delta F_x &= \iint_S \frac{x(\vec{n}\cdot\vec{M})}{(x^2+y^2+z^2)^{3/2}}\, dS \\ \Delta F_z &= \iint_S \frac{z(\vec{n}\cdot\vec{M})}{(x^2+y^2+z^2)^{3/2}}\, dS \end{aligned} \tag{2}$$

where $\vec{n}$ is the outward normal unit vector at the element of surface area dS, and the origin of the coordinate system x, y, z is at the point of observation (see Figure 11).

If S is a finite closed surface the integrand is a multi-valued function of x and y. However, it may be made single-valued by dividing the closed surface S into appropriate surfaces S_1, S_2, $\cdots$, and integrating over the separate surfaces.

These integrals may be transformed into integrals with respect to x and y alone. Let the angles of the unit normal, $\vec{n}$, with respect to the x, y, and z axes be α, β, γ, then $dS = dS_h/\cos\gamma$ where dS_h is the projection of dS on the x, y plane, so $dS = dxdy/\cos\gamma$ $(\vec{n}\cdot\vec{M}) \equiv \sigma_S$, the free magnetic charge per unit area on the

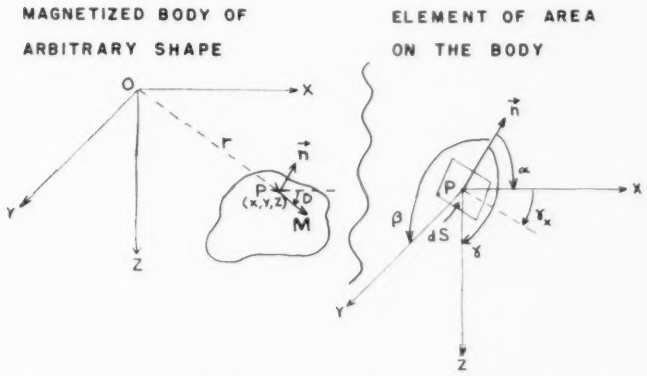

FIG. 11. Coordinates locating a magnetized body of arbitrary shape, and the unit normal on an element of its surface.

surface dS. $\sigma_{S_h} \equiv \sigma_S / \cos \gamma$, the free magnetic charge per unit horizontal area on the surface dS. Substituting in (2) we get

$$\Delta F_x = \sum_{S_j} \iint_{x_j y_j} \frac{x \sigma_{S_h} dx dy}{(x^2 + y^2 + z^2)^{3/2}}$$
$$\Delta F_z = \sum_{S_j} \iint_{x_j y_j} \frac{z \sigma_{S_h} dx dy}{(x^2 + y^2 + z^2)^{3/2}} \tag{3}$$

where $z = z(x, y)$. However $\sigma_S = \cos \alpha \, M_x + \cos \gamma M_z$ so

$$\sigma_{S_h} = \frac{\cos \alpha}{\cos \gamma} M_x + M_z. \tag{4}$$

γ is also the dip angle of the element of surface dS. We define γ_x as the apparent dip, or the dip angle of the element of surface, in the x direction. Since the projection $\vec{n}$ on the x, y and z axes are $\cos \alpha$, $\cos \beta$, and $\cos \gamma$ respectively, $\tan \gamma_x = \cos \alpha / \cos \gamma$. Equation (4) becomes

$$\sigma_{S_h} = \tan \gamma_x M_x + M_z. \tag{5}$$

The terms of the integrand are finite if the body does not have vertical sides on the north or south ($\gamma_x \neq \pi/2$), and if the point of observation is never on the surface of the body ($x^2 + y^2 + z^2 \neq 0$). Under these circumstances numerical evaluation of the integral is quite simple. We now expand $z(x, y)$ as $z = z_D + e\,(x, y)$ where z_D takes discrete values and e will be small enough so that it may be neglected.

$$\Delta F_x = \sum_{S_j} \iint_{x_j y_j} \frac{x\sigma_{S_k} dxdy}{(x^2 + y^2 + z_D{}^2 + 2ez_D{}^2 + e^2)^{3/2}}$$
$$\Delta F_z = \sum_{S_j} \iint_{x_j y_j} \frac{(z_D + e)\sigma_{S_k} dxdy}{(x^2 + y^2 + z_D{}^2 + 2ez_D + e^2)^{3/2}}. \tag{6}$$

We can neglect the e terms and later evaluate their approximate contribution. For the case where σ_{S_k} is a constant over segments of x, y (e.g. for truncated pyramids) the contribution from the given segment j is

$$\Delta F_{x_j} = \sigma_{S_{kj}} \iint_{x_j y_j} \frac{xdxdy}{(x^2 + y^2 + z_D{}^2)^{3/2}}$$
$$\Delta F_{z_j} = \sigma_{S_{kj}} \iint_{x_j y_j} \frac{z_D dxdy}{(x^2 + y^2 + z_D{}^2)^{3/2}}. \tag{7}$$

The integrals give the component attractions for a sheet of charge $\sigma_{S_{kj}}$; distributed over a segment S_j which lies at a depth z_d.

Remembering that the attraction at a point of a sheet of charge of unit strength distributed over a given area is the same as the average attraction over the same area of a unit charge at the original point of observation, we can quickly evaluate integrals of the form

$$\iint_{xy} \frac{xdxdy}{(x^2 + y^2 + z_D{}^2)^{3/2}} \quad \text{and} \quad \iint_{xy} \frac{z_D dxdy}{(x^2 + y^2 + z_D{}^2)^{3/2}}. \tag{8}$$

This is done by mapping on a suitable scale the integrands

$$\frac{x}{(x^2 + y^2 + z_D{}^2)^{3/2}} \quad \text{and} \quad \frac{z_D}{(x^2 + y^2 + z_D{}^2)^{3/2}}.$$

The map can be made to as high a precision as necessary. The average value for a given arbitrary segment of the map can be found by inspection. Thus tables are quickly constructed for the values of expressions (8) for square elements at various positions.

This operation has been carried out, using an arbitrary unit of length, for an element of area which is a $\frac{1}{2} \times \frac{1}{2}$ square at depths z_D, equal 5/6, 1, 5/4 and 5/3. The resultant tabulation of expressions (8) has been made for half integral values of x_j and y_j, with x_j ranging from $+6.0$ to -6.0 and y_j from $+4.5$ to -4.5. From this tabulation numerical results for equation (6) can be obtained by direct summation, neglecting terms in e.

The approximate error from neglecting e in (6) can be evaluated. Equation (6) becomes

$$\Delta F_x = \sum_{S_j} \iint_{x_j y_j} \frac{\sigma_{S_k} x}{(x^2 + y^2 + z_D^2)^{3/2}} \left\{ 1 - \frac{3}{2} \frac{\left(\frac{2e}{z_D} + \frac{e^2}{z_D^2}\right)}{\left(\frac{x^2 + y^2}{z_D^2} + 1\right)} + \frac{15}{8} \frac{\left(\frac{2e}{z_D} + \frac{e^2}{z_D^2}\right)^2}{\left(\frac{x^2 + y^2}{z_D^2} + 1\right)^2} - \cdots \right\} dx dy$$

$$\Delta F_z = \sum_{S_j} \iint_{x_j y_j} \frac{\sigma_{S_k} z_D}{(x^2 + y^2 + z_D^2)^{3/2}} \left\{ 1 + 3 \frac{\left(\frac{e}{z_D} + \frac{3}{2}\frac{e^2}{z_D^2} + \frac{1}{2}\frac{e^3}{z_D^3}\right)}{\left(\frac{x^2 + y^2}{z_D^2} + 1\right)} + \frac{15}{8} \frac{\left(\frac{4e^2}{z_D^2} + \frac{3e^2}{z_D^3} + \frac{3e^4}{z_D^4} + \frac{e^5}{z_D^5}\right)}{\left(\frac{x^2 + y^2}{z_D^2} + 1\right)^2} - \cdots \right\} dx dy \tag{9}$$

Defining

$$a \equiv \frac{e}{z_D} \quad \text{and} \quad b \equiv \frac{1}{\frac{x^2 + y^2}{z_D^2} + 1}$$

we can write equation (9) as

$$\Delta F_x = \sum_{S_j} \iint_{x_j y_j} F_{x_0}'(1 + K_x) dx dy$$
$$\Delta F_z = \sum_{S_j} \iint_{x_j y_j} F_{z_0}'(1 + K_z) dx dy \tag{10}$$

where

$$K_x = -3ab - \frac{3}{2}a^2 b + \frac{15}{2}a^2 b^2 + \cdots$$
$$K_z = +a - 3ab - \frac{9}{2}a^2 b - \frac{3}{2}a^3 b + \frac{15}{2}a^2 b^2 + \cdots \tag{11}$$

To estimate the error we can simplify the error terms as follows

$$\iint_{x_j y_j} F_{z_0}' K_z dx dy \cong \sum_{A_i} \iint_{x_i y_i} F_{z_0}' dx dy \frac{\iint_{x_j y_j} K_z dx dy}{A_i}$$
$$\iint_{x_j y_j} F_{z_0}' K_z dx dy \cong \sum_{A_i} \iint_{x_i y_i} F_{z_0}' dx dy \frac{\iint_{x_i y_i} K_z dx dy}{A_i} \qquad (12)$$

where A_i is the ith elementary square $\frac{1}{2} \times \frac{1}{2}$ on a side.

For a limited number of positions of the origin relative to the body, the approximate average value of a and b can be found for the elements of area A_i. Then the approximate value of the error as given by equation (10) may be found using the simplification of equation (12).

The anomaly expected from Caryn Peak has been calculated in this manner. Caryn Peak is represented as a truncated pyramid rising from an ocean floor 2.6 nautical miles (n. m.) deep. It is 6.24 n. m. square at the base, 0.63 n. m. square

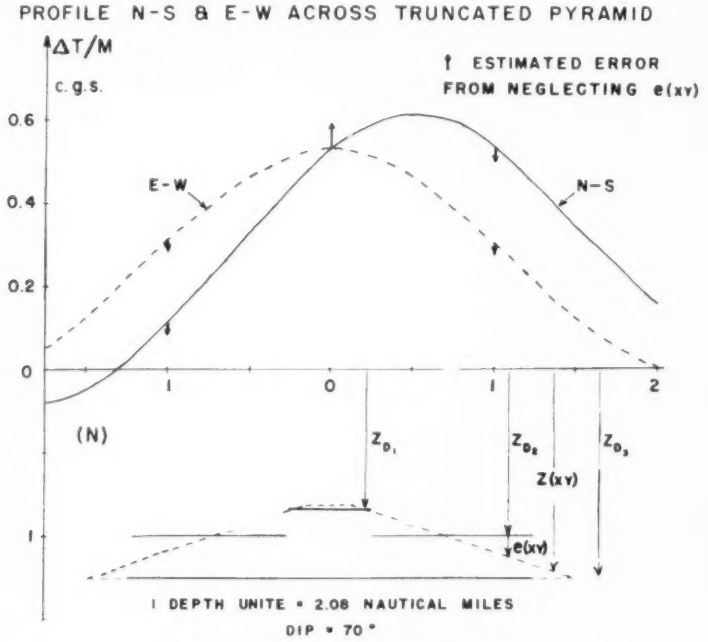

FIG. 12. The total intensity anomaly for a truncated pyramid found by graphical integration for discrete depths.

at the top at a depth of 1.7 n. m., thus its sides slope N., E., S., and W. at a dip of 17.3° (see Figure 12). When the depth unit (D. U.) is 2.08 n. m., then from previously obtained tabulation for expression (8) giving the attraction for a square, A_i, $\frac{1}{2}$ a D. U. on a side at depths of 5/6, 1 and 5/4 D. U. at various half integral values of x_i, y_i to the center, the anomaly was obtained by direct summations for a magnetization parallel to the main field which dips at 69.2°.

This is presented in Figure 9 where the magnetization has been set at .0058 cgs in order to produce a maximum anomaly of 350 gammas.

The approximate value of the error from neglecting terms in e has been calculated for points located over the center and at 2.08 miles north, east, south and west of the seamount. Defining the relative error as the result of this evaluation divided by the calculated anomaly at the same point we find it is .11, −.29, −.11, −.07, and −.11 for the respective points. The proportional error in terms of the maximum anomaly is .10, −.06, −.06, −.06, and −.06 for the respective points. The proportional error is more significant in considering the general accuracy of the calculated anomaly map. In any case these results show that for the purposes of evaluating the magnetization of the seamount the method of computing the anomaly is sufficiently accurate.

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GEOPHYSICS, VOL. XXI, NO. 2 (APRIL, 1956), PP. 433–454, 16 FIGS.

PROSPECTING FOR CHROMITE WITH GRAVIMETER AND MAGNETOMETER OVER RUGGED TOPOGRAPHY IN EAST TURKEY*

SULHI YÜNGÜL†

ABSTRACT

From 1952 to 1954 gravity and magnetic surveys were made in Turkey over the concessions of the Eastern Chromite Works to discover new chromite reserves in a region of rugged topography and complicated geology. As a result of these surveys a new chromite ore body of 250,000 tons was discovered at the bottom of an open cut beneath a thin horizontal sheet of chromite.

It is shown that gravity prospecting is a more promising technique for locating relatively large chromite masses, even over rugged topography, than might have been expected. The terrain corrections, which constitute the major part of the computations, must be simplified and it is important that the correct surface densities be employed. In addition, difficulties arizing from the high and variable magnetic susceptibilities in serpentines must be surmounted. The mass of chromite estimated from the gravity results agrees well with the amount found by subsequent drilling.

INTRODUCTION

The geophysical literature reports the results of a gravity survey (Hammer, Nettleton, and Hastings, 1945) and several magnetic surveys (Hawkes, 1951) over chromite deposits. As far as the present writer knows, however, there are no published accounts of gravity surveys for chromite over rugged terrain. In the paper by Hammer et al. it is stated that: " . . . moderate or severe topography probably would make such work impossible because of the low relief of expected anomalies . . . ". Considering the fact that most of the world's chromite reserves are found in topographically rugged regions, it was thought that the publication of our results in Turkey, over an area of high topographic relief, would be helpful. The area where our work was carried on should be particularly interesting since it is the principal locality at which the famous Turkish chromite deposits are mined.

From September, 1952, to October, 1954, systematic gravity and magnetic surveys were made in five concessions of the Eastern Chromite Works, which is a branch of Etibank, an organization financed by the Turkish government to exploit large mineral resources. The concessions are named Guleman, Kündikan, Sori, Bagin, and Herpit Yayla. (see Fig. 1, a geographical map). They lie within an area of 300 square kilometers. The mine city, at 39° 52′ E. longitude and, 38° 28′ N. latitude, lies about 55 km east-southeast of the city of Elazig.

Of six separate areas surveyed, all were surveyed with both gravimeter and magnetometer except for the surveyed area in the Herpit Yayla concession, which was surveyed with the magnetometer only.

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FIG. 1. Geographical map. The heavy crosses indicate the locations of the concessions surveyed (G: Guleman; K: Kündikan; S: Sori; B: Bagin; H: Herpit Yayla).

GENERAL GEOLOGY

In the concessions of the Eastern Chromite Works, chromite is found in the midst of a large region of igneous ultrabasic and basic rocks, usually in dunite serpentines, and sometimes in rhombic pyroxene serpentines of various degrees of alteration. Peridotites, harzburgites, and norites are abundant. Also found in this region are phyllite-chloritic schist-quartz series, green-red schists, limestones, marbles, sandstones, conglomerates, and red serpentine breccias. Transitions between dunites, harzburgites, pyroxenites, and norites are observed clearly. After the ultrabasic silicates were crystallized, the chromite, still in liquid form, was in many cases injected into the ultrabasic rocks. Post-crystallization tectonic movements were intense and sometimes broke the chromite masses. The strongest serpentinization occurred between large chromite masses and the adjacent peridotitic rocks, possibly because the competent chromite masses crushed the peridotites during tectonic movements thus rendered the latter more susceptible to serpentization. Extremely altered "talc serpentine," in the form of soft, gray, clay-like material, is found under some of these chromite masses, so that the chromite appears to be "floating" on this material.

In the Guleman and Kündikan concessions, according to G. Rosier (1939), overthrust sheets consisting of serpentine, gabbros, crystalline schists, and

marbles overlie normal sedimentary rocks of upper Cretaceous age. To the north, in the Sori concession, occurs a large massif composed of material identical to that of these overthrust sheets. Although many geologists, such as Rosier (1939) and Borchert (1952), have studied the concession areas, opinions as to the tectonic and age relationships are diverse and contradictory.

The difficulties for geophysical work created by the complicated geology are great, but the critical factor is the rugged topography, which is treated below.

The known and exploited chromite deposits of this region are among the largest and richest chromite masses of the world. The forms of the chromite ore bodies vary from shapeless masses, locally called "heads," which occur in the Guleman and Kündikan concessions, to pseudo-veins, which are usually found in the Sori concession. The tonnages of the largest known chromite masses range from about 100,000 tons to 1,100,000 tons. As an example of the characteristics of the chromite ore, the properties for the Gölalan chromite mass—the largest mass of all—are as follows:

Average grade (Cr_2O_3)	51.60 percent
Specific gravity	4.15
FeO content	16.00 percent
Iron/chromium ratio	1/2.84

PHYSICAL PROPERTIES OF THE ROCKS

Surface Densities

Density measurements were made in the laboratory for many rock specimens taken at the surface or from mining cuts. As an example of the data obtained, the density values for specimens taken in the Guleman and Kündikan concessions, which are about 2 km apart, are given in Table I. Some rock types show a wide range of densities because of their lack of mineralogical uniformity even within the same area.

Magnetic Susceptibilities

Susceptibility measurements made on rock and mineral specimens from the vicinity of the Gölalan chromite mass in the Guleman concession are shown in Table II. The measurements were made by placing one gram of the powdered

TABLE I

SURFACE DENSITY VALUES OF ROCK AND MINERAL SPECIMENS IN THE GULEMAN AND KÜNDIKAN CONCESSIONS

Name of Material	No. of Samples	Density Range	Average Density
Serpentine	39	2.40–2.78	2.50
Norite (Gabbro)	20	2.86–3.10	2.95
Phyllite-sandstone	6	2.54–2.79	2.70
Marble-limestone	4	2.67–2.78	2.70
Quartzite-quartzite schist	4	2.56–2.63	2.60
Epidote-quartz schist	2	3.04–3.08	3.06
Harzburgite	6	2.78–3.07	2.85
Chromite	8	3.74–4.19	4.00

TABLE II

MAGNETIC SUSCEPTIBILITY VALUES FOR SPECIMENS IN VICINITY OF GÖLALAN MASS, GULEMAN CONCESSION

Name of Material	No. of Samples	Range of Susceptibility Factor in Milligrams	Average Susceptibility Factor in Milligrams
Black serpentine	15	65–125	90
Harzburgite (little serpentinized)	6	55–195	85
Green serpentine (with chrysotile)	26	5–110	50
Dunite	1	30	30
Norite-Gabbro	9	0– 75	10
Chromite	25	3– 45	5

Values taken from an unpublished report by Kovenko (1942).

specimen in a certain magnetic field and measuring the increase of weight in milligrams. The values in Table II are in good agreement with the average values of measured and calculated susceptibilities found in the literature.

Vertical intensity measurements made with a magnetometer on one-decimeter cube specimens of natural rock from the same area are shown in Table III in terms of the readings, in gammas, observed on the magnetometer. The total effect of induced and permanent magnetization were determined.

Although the magnetic susceptibility of chromite is *lower* than that of serpentine, chromite should give positive anomalies, provided the direction of permanent polarization is suitable. In the region studied, magnetic highs observed over chromite masses are attributed to the permanent magnetization of the chromite. For this reason, tests on hand specimens with magnetometers were regarded as more reliable than elaborate susceptibility determinations.

The high and variable susceptibilities of the serpentine are noteworthy. It is generally believed that high susceptibilities in serpentines are due to secondary magnetite formed during serpentinization, and that the higher the degree of alteration (up to a certain limit), the greater the concentration of magnetite. Some of the geologists and mineralogists whom the writer consulted on this subject, however, believe that the magnetite is primary, that it remained in its original state while the peridotite mass was serpentinized, and that the concentration of magnetite was effected by the shrinking of the original peridotite volume, as well as by local concentrations that existed originally. A solution of this unsolved problem will provide help in evaluating magnetic anomalies in serpentine areas.

TABLE III

Name of Material	No. of Samples	Range in Gammas	Average in Gammas
Chromite	3	34–43	38
Serpentine	5	9.8–21	14

INSTRUMENTS AND FIELD TECHNIQUES

For the gravity surveys, a model F-27 Atlas gravimeter with a sensitivity of 0.009977 to 0.010068 mg per dial division, was used. Only 3.6 per cent of the measurements were repeated because of excessive drift. The errors of closure of the base loops, consisting of four bases, ranged between zero and +0.02 mg. and averaged +0.016 mg. The probable error of a single reading of this instrument, according to the manufacturer, is about 0.015 mg. A total of 9,602 gravity stations were occupied over an area of 348 hectares.[1]

Except in areas of abrupt surface features, the gravity stations were located at the corners of a regular grid pattern. Depending on the size of the ore bodies usually found in the area being surveyed, the station spacing was 20 meters in most areas, but 15 or 10 meters in some areas. In areas where pseudo-vein deposits were expected, the gravity stations were taken at 10-meter intervals along regular profiles spaced 30 meters apart, the profiles running perpendicular to the probable strike of the vein.

For the magnetic surveys, an Askania Schmidt magnetometer, Type GF-6, with a sensitivity of about 25 gammas per dial division, was used for the measurement of vertical magnetic intensities only. A total of 17,694 magnetometer stations were occupied over an area of 354 hectares. Twice as many magnetic measurements as gravity measurements were usually taken, because magnetic readings were taken both at the already-established gravity-station pegs and also at the midpoints between the gravity stations.

THEORETICAL CONSIDERATIONS

Except at Herpit Yayla, the difficulties encountered with the variations of the magnetic susceptibilities of the serpentine vitiated any quantitative interpretation of the observed magnetic anomalies in the areas studied.

Quantitative estimates of the mass of chromite ore causing the gravity anomalies, however, were possible in this area because of the large size of the masses. To estimate quickly the depths and masses from second vertical derivative gravity maps (Elkins, 1951), as was done for the many small gravity anomalies found in this area, charts were prepared for a sphere and a horizontal cylinder. Using charts such as the sample shown in Figure 2, these estimates were made in a matter of seconds.

For the second vertical derivative gravity maps, the equations for a sphere are:

$$Z = 1.225\rho_0 \tag{1}$$

$$R = (Z^4 G_m / 8\pi\sigma\gamma)^{1/3}. \tag{2}$$

Here Z is the depth to the center, ρ_0 is the radius from the maximum to the zero position on the second derivative map, R is the radius of the sphere, σ is the density contrast, γ is Newton's universal constant of gravitation, and G_m is the

[1] A hectare is approximately 2.471 acres.

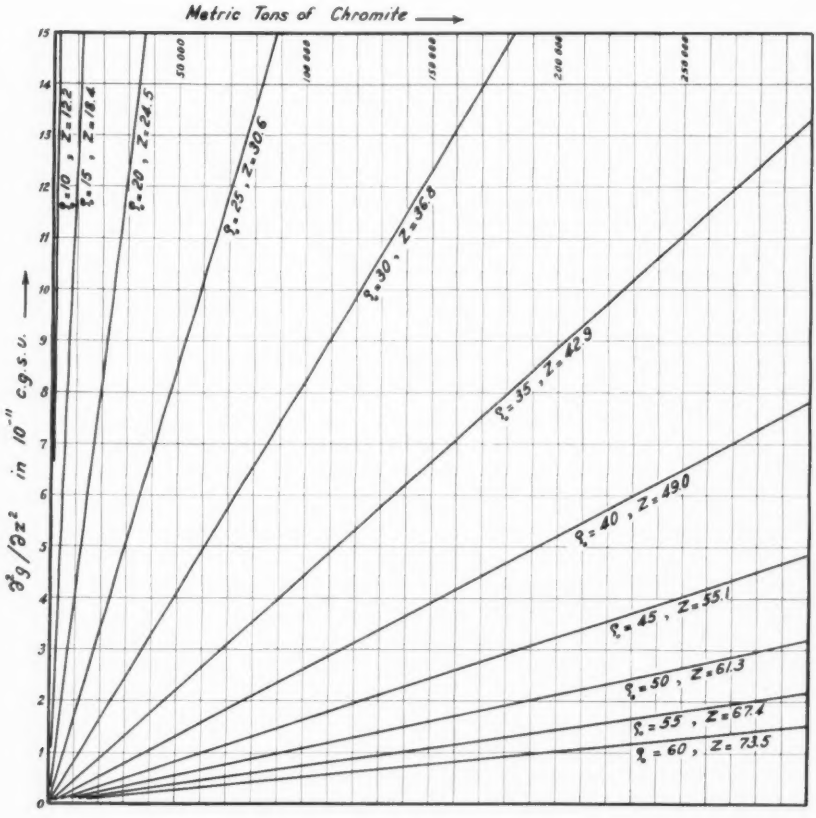

FIG. 2. Depth and mass estimation of spherical chromite bodies in serpentine. Z = depth to center in meters, ρ_0 = radius of gravity second derivative anomaly in meters. Densities of chromite and serpentine are 4.0 and 2.5, respectively.

maximum value of the second derivative. From these equations, a special equation for chromite in serpentine, for which the densities are 4.0 and 2.5, respectively, was found to be simply

$$M = .015\rho_0{}^4 G_m \tag{3}$$

where M is the mass of chromite in metric tons, ρ_0 is in meters, and G_m is in 10^{-11} c.g.s. units.

To estimate more accurately the masses of the chromite, as was done for the larger, more important gravity anomalies, the method of Hammer (1954) was

used. In this method the mass of the chromite, for the same assumed density contrast, is:

$$M = 0.638 \sum S^2 \Delta g \qquad (4)$$

where Δg is the anomalous gravity value in 0.01 mg units associated with the small area S^2. The similarity of equations (3) and (4) is noteworthy.

Limitations of the Gravity Survey

It will be shown in a later section that the rugged topography imposed on the reduced gravity value of each station an estimated probable error of about 0.15 mg, so that the total probable error of each station was no more than 0.2 mg. Thus we could hope to isolate reliably only those gravity anomalies greater than 0.2 mg.

The relation between maximum gravity anomalies, tonnage, and depth to

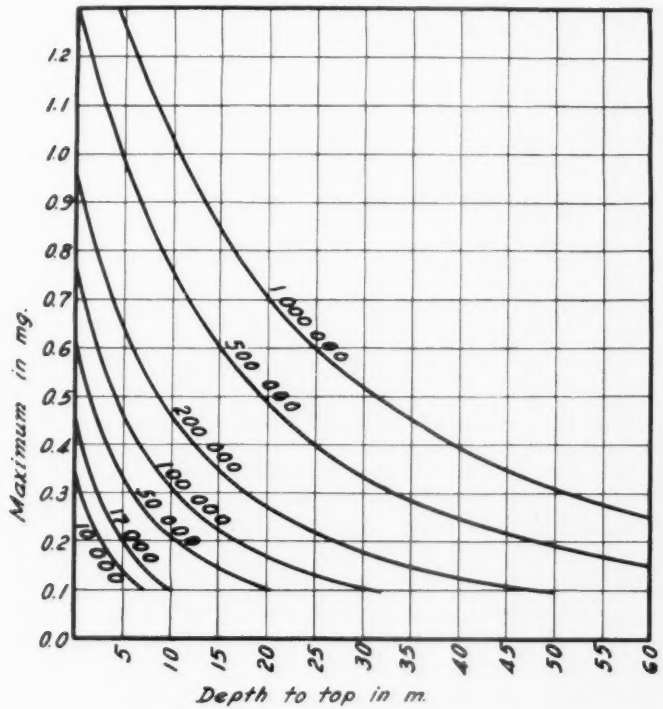

FIG. 3. Maximum gravity anomalies caused by spherical chromite bodies in serpentine. Masses (in metric tons) are indicated by figures on curves. Density of chromite is 4.0 and that of serpentine is 2.5.

the top of spherical chromite bodies in serpentine country rock (with an assumed density contrast of 1.5) is shown in Figure 3.

With 0.2 mg precision and with the station spacings used, 20,000 tons of chromite at a depth (to the top) of about 5 meters, 100,000 tons at 20 meters, and 200,000 tons at 30 meters could be detected. Chromite masses of about 200,000 tons are common in the Guleman concession. A spherical chromite mass of 200,000 tons at a depth (to the top) of 48 meters, however, would create a maximum of 0.1 mg, but the 0.05 mg contour would include about 23 stations, if a 20-meter grid is used in the field station measurements. As the number of minus and plus random errors are increased, these would tend to equal each other, rendering $\sum \Delta g S^2$ (Hammer, 1945) close to its correct value. Thus large masses lying below the prefixed depth limits could probably be discovered with a gravity survey.

REDUCTION OF GRAVITY DATA

The gravimeter readings were corrected for drift and latitude in the conventional manner.

In the Guleman and Kündikan concessions a total elevation correction factor of 0.2 mg per meter, corresponding to a surface density of 2.595, was used for all stations. This choice was based on the values of the average densities of the various rocks constituting the country rock, as obtained from laboratory measurements shown in Table I. In other concessions we were able to make use of density profiles (Nettleton, 1940) also. The surface densities for the five areas surveyed ranged from 2.4 to 2.6.

Terrain Corrections

The typical terrain-correction problems caused by the rugged topography in the survey areas are exemplified by the surveyed area in the Guleman concession. Here the topographic relief in the grid area itself (162 hectares), where the gravity stations were located, was about 260 meters; the topography commonly included ravines 20 to 50 meters deep, with ridges between them, and open cuts and waste dumps with 20 to 30 meters of relief, as well as larger hills 70 to 100 meters high. The flanks of a circular mountain (Fakir Kitan) were included within the grid area; it had an abrupt topographic relief of 440 meters above the mean surface level.

The effect of large and distant features, rendered critical by abrupt elevation differences in the grid area, constituted the main problem in terrain corrections. The station-elevation factor related to distant features varied considerably within the grid area.

Terrain corrections were carried out to and including zone I (outer radius of 4,469 meters) of Hammer's (1939) zone chart, but a modification of the standard techniques was made in order to reduce the amount of labor involved and to avoid erratic variations in chart readings for distant features. The terrain cor-

rections for zones B, C, and D of Hammer's chart were made for each gravity station in the usual manner from 1/1,000 scale maps by placing the center of the zone chart on each individual station. The terrain correction chart readings for zones E and F were made essentially simultaneously for each 5-station group of gravity stations (indicated by dashed squares in Fig. 4) from 1/5,000 scale maps by placing the center of the zone chart only over the station forming the middle

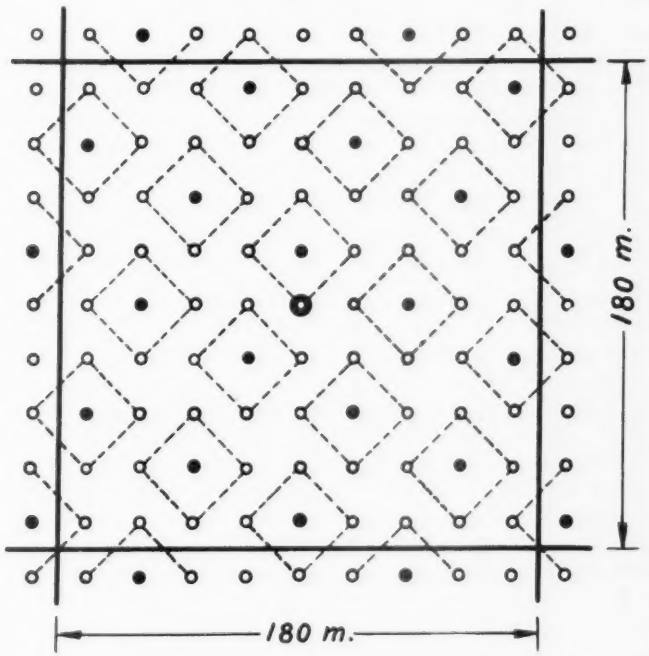

FIG. 4. A 180 by 180 meter square showing gravity stations and *E*, *F* zones groups. Station spacing is 20 meters. Double circle is *G*, *H*, *I* zones chart reading point.

of each 5-station group (indicated by the station with a solid dot in Fig. 4). The elevations of the zone E and F compartments obtained in this way for all five stations of the same group were used on the assumption that the respective compartment readings would vary only a negligible amount by shifting the center of the chart 20 meters in either direction, however, the actual elevation of each station is treated separately in obtaining the difference in elevation between the compartment and the individual station. The terrain correction chart readings for zones G, H, and I were made essentially simultaneously for 81 stations (or 16 five-station groups)—indicated by the square formed by the heavy solid line in

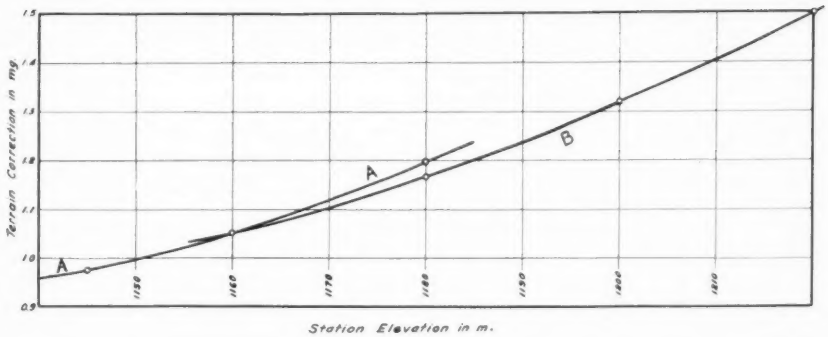

FIG. 5. Terrain correction graphs for zones *G*, *H* and *I* for two adjacent squares *A* and *B*. ($\sigma = 2.0$).

Figure 4—from 1/25,000 scale maps. This was done by placing the center of the zone chart over only the station forming the center of the square (indicated by the double circle in Fig. 4) and, as before, using the elevations of the zone G, H, and I compartments obtained from the chart for all 81 stations. Each station, however, was treated separately according to its individual elevation. After the compartment elevations for zones G, H, and I were double checked to insure greater precision, the total terrain correction for these three zones only was computed for about four elevation values covering the elevation range in the individual square being studied. The four values were plotted to give a curve of terrain correction vs station elevation for that square alone (see curve B, for example, in Fig. 5). The points fell on a smooth curve and, as a consequence, the total terrain corrections of zones G, H, and I could be read from this curve for all the gravity stations within the square. Figure 5 shows sample terrain correction vs station elevation curves for two adjacent squares, A and B. For the stations near the side common to two adjacent squares, the differences between the terrain correction found from the curves of the respective squares varied between 0.00 and 0.05 mg. When this difference was greater than 0.02 mg a "passage correction" was applied.

Table IV gives a sample of the typical terrain corrections for a gravity station in the surveyed areas.

TABLE IV

TYPICAL TERRAIN CORRECTIONS IN THE SURVEYED AREAS

Zones	Total Correction in mg
B	0.091
C	0.134
D	0.436
E	0.268
F	0.475
G–H–I–	1.871
Total	3.275 mg

The modification of the techniques of making the terrain corrections reduced the chart reading about 80 per cent for zones E and F, and about 97.5 per cent for zones G, H, and I.

RESULTS OF THE SURVEYS

Kündikan Concession

According to geological studies by Borchert (1952), the possibility of discovering large masses of chromite in the Kündikan concession was small. Here several very small, widely scattered masses were known, but the only important

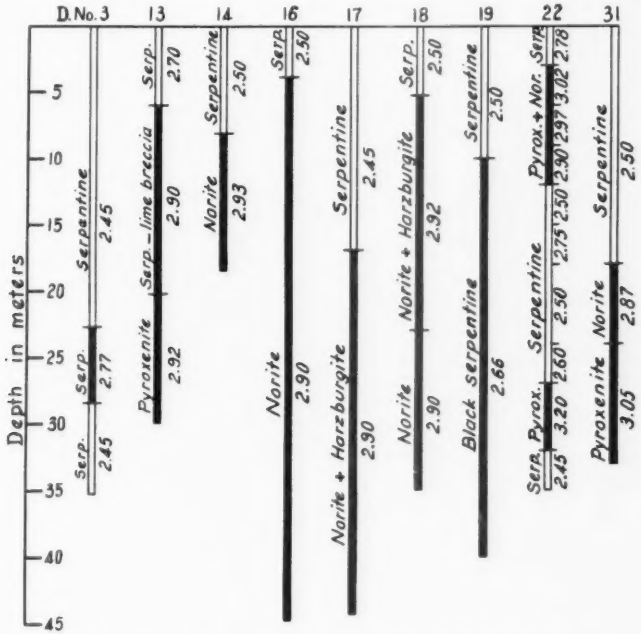

FIG. 6. Kündikan drill logs. Black parts indicate relatively dense media. Figures refer to densities in intervals shown.

chromite mass ever found was a body of only about 40,000 tons. Nonetheless geophysical work was desirable before abandoning the area because of the proximity to the mine installations in case a large body was discovered.

Initial tests in the area were made to delineate the 9,500 tons of chromite still unmined in the main chromite mass, and to search for other possible masses associated with it. By taking detailed gravity stations on a 10-meter grid, a good gravity correlation was obtained—in spite of the mine cut, which was steep, and

17 meters deep; but no other favorable anomaly was obtained in this test area. The magnetic anomaly map was erratic; it had little visible relation to the chromite mass but reflected mainly the shape of the mine cut.

The presence of a gravity high and the absence of a magnetic high over the main chromite mass encouraged the drilling of nine gravity highs found in various parts of the Kündikan concession. Of the nine gravity highs tested in 1953, four coincided with magnetic lows, two coincided with magnetic dipole-type anomalies, one coincided with a magnetic high (D. No. 13, Figures 6 and 7), and two occurred in areas with no characteristic magnetic anomaly. The drill logs of each

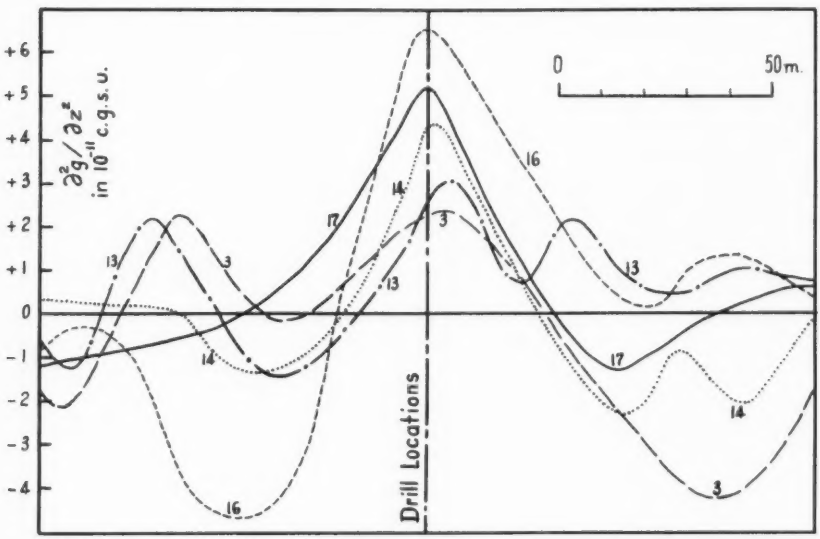

FIG. 7. Kündikan Concession, gravity second derivative profiles over drill holes. Curves are marked with drill hole numbers. (3, 13, 14, 16, 17.)

of the nine holes that tested these nine anomalies (see Fig. 6) show that relatively dense material was found beneath every gravity high. Usually, norite was found beneath a gravity high coinciding with a regular magnetic low. The occurrence of isolated norite masses lying beneath serpentines had been considered improbable by many geologists prior to the drilling. The gravity second derivative profiles over five of the above-mentioned drill holes are shown in Figure 7.

The results emphasized that detection of relatively dense masses enclosed in serpentines by gravimeter was satisfactory, that most of the gravity highs were caused by norite masses under serpentines, and that there was a good chance to identify these norite masses by the fact that they usually created regular magnetic lows.

Herpit Yayla Concession

Here only a magnetic survey was made and a number of favorable anomalies were found. The test profiles over the existing chromite outcrops (Fig. 8) indicated that the chromite masses created regular magnetic highs. Although the

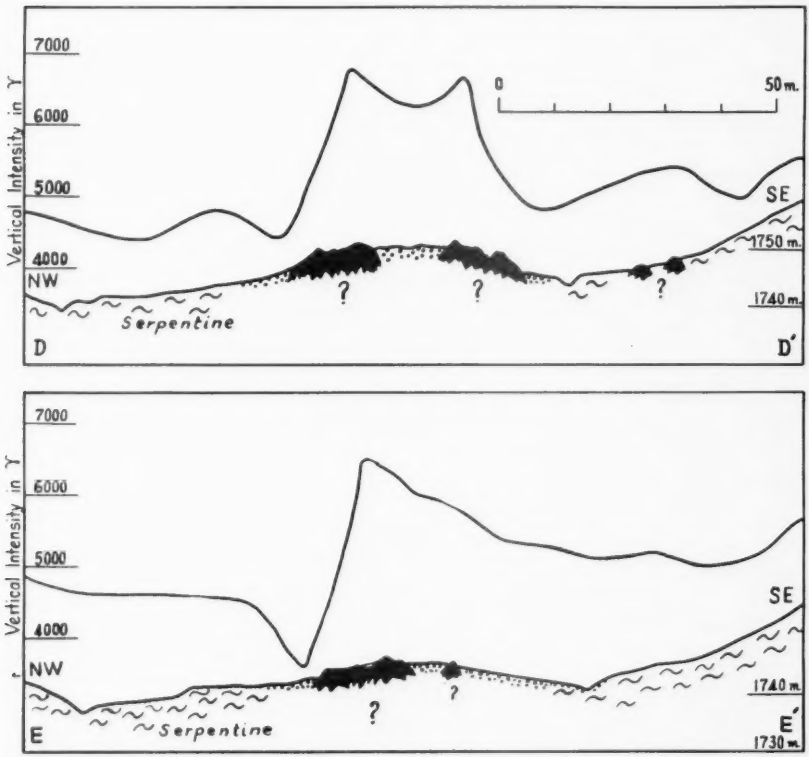

FIG. 8. Herpit Yayla Concession, vertical intensity magnetic profiles and cross-sections, as of 1953. Black areas: massive chromite; dotted areas: chromite placer.

area has not yet been drilled, the magnetic anomalies will probably assist in directing any future drilling campaign.

Guleman Concession

Of the five concessions surveyed, the Guleman concession contained by far the largest chromite ore bodies. Prior to the present geophysical surveys, four separate chromite ore bodies, with original tonnages of 850,000, 530,000, 293,000, and 144,000 tons, respectively, were known to occur within a 40 hectare tract in

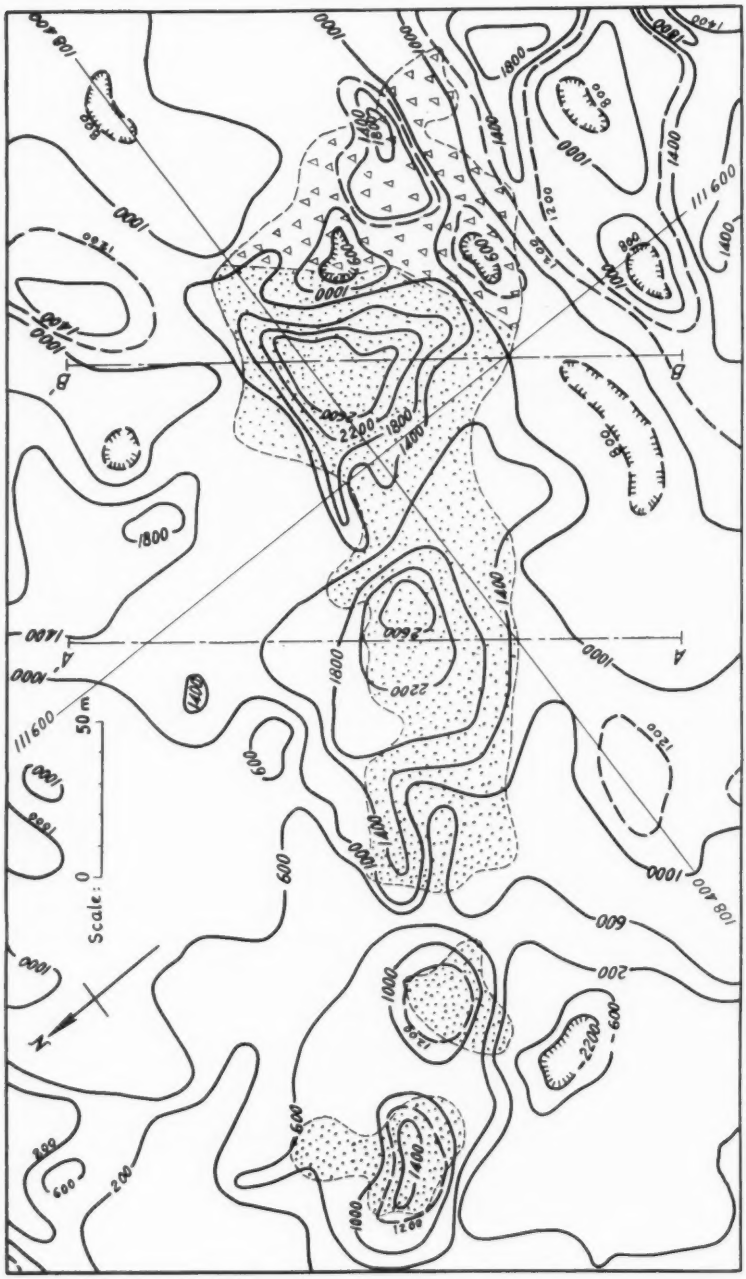

FIG. 9. Guleman Concession, Gölalan Mine 1941 magnetometer survey, vertical intensity contours in gammas. Dotted area indicates outline of massive chromite and area with triangles indicates outline of broken chromite, as determined by subsequent drilling.

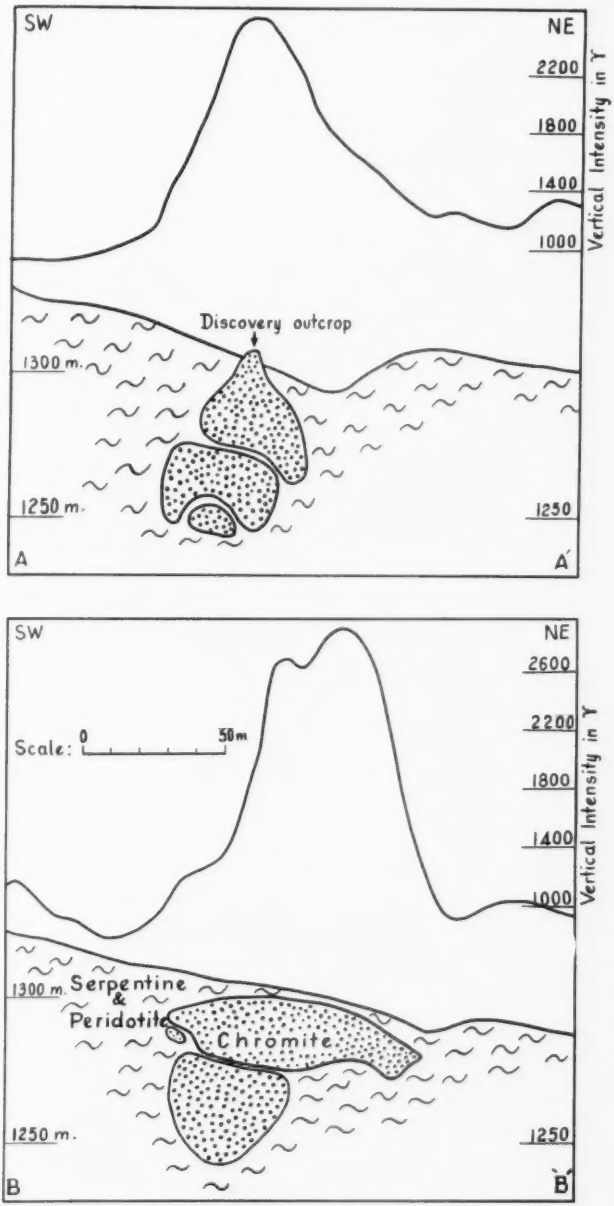

FIG. 10. Gölalan, vertical intensity magnetic profiles and geologic sections, as of 1941. (The lower mass in Cross-section *BB'* was discovered by the recent gravity and magnetic surveys.)

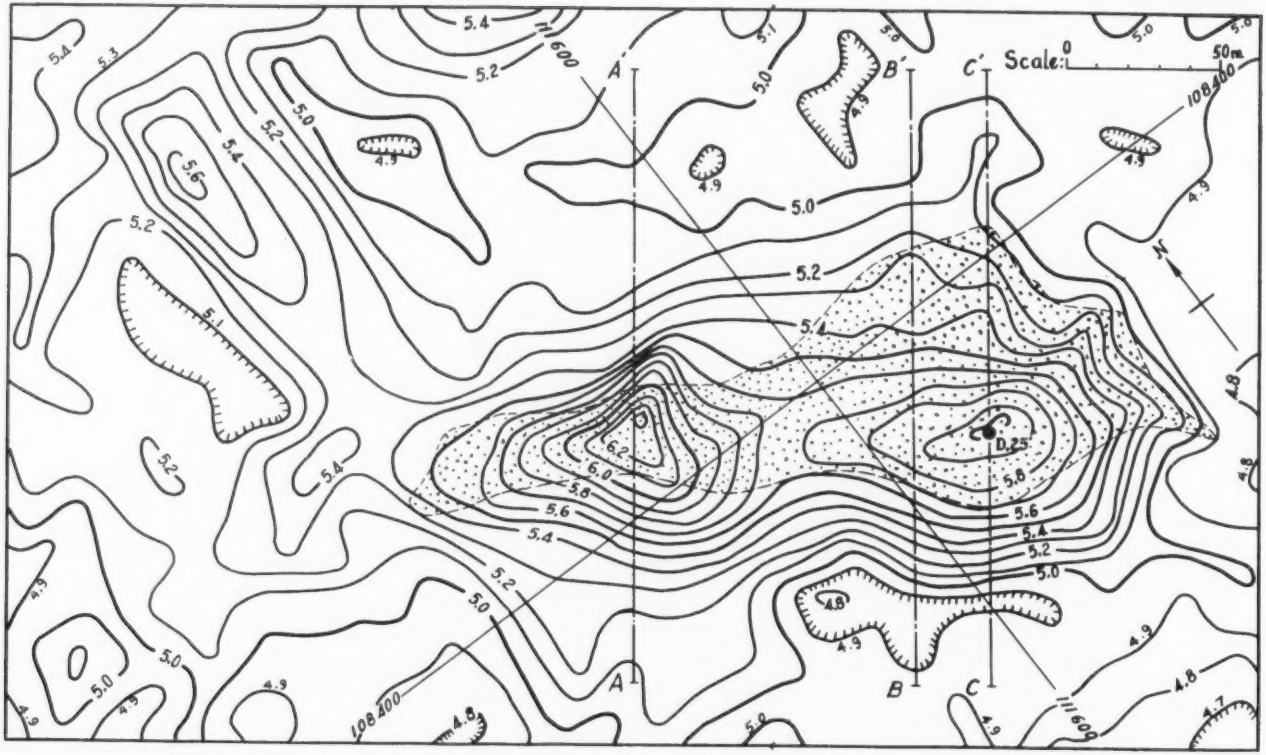

FIG. 11. Gölalan, Bouguer anomaly with terrain corrections, and the outcrop of remaining chromite, as of 1953. Surface density $\sigma = 2.6$; contour interval 0.1 mg.

this concession. As of January 1, 1953, 1,300,000 tons of chromite had already been mined from these four bodies. The largest of these masses was the Gölalan mass.

The Gölalan chromite mass, the largest in the concession, was discovered in outcrop before 1940. In 1941, a magnetic survey in the outcrop area, made by

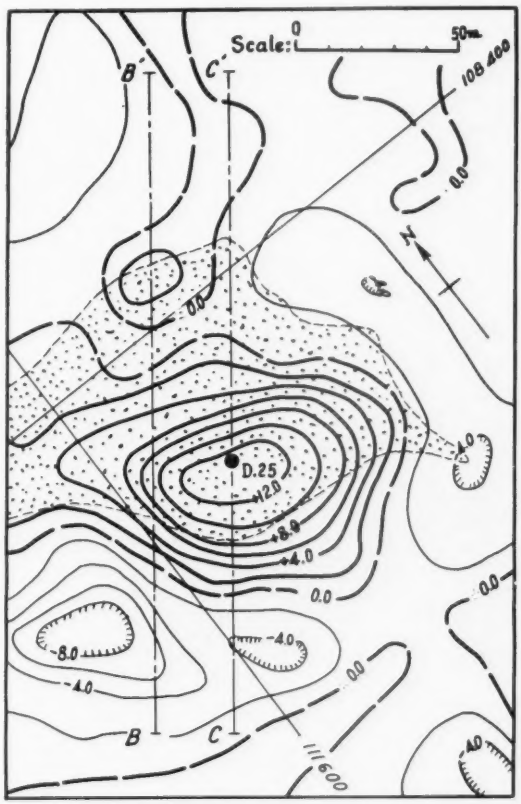

FIG. 12. Gölalan, gravity second derivative for $\sigma = 2.6$. Contour interval 2×10^{-11} c.g.s.u.

Maden Tetkik ve Arama Enstitüsü under the supervision of J. J. Breusse, indicated a large chromite mass (Figs. 9 and 10). Physical development work, which consisted of stripping operations and the drilling of 108 boreholes, resulted in a measured tonnage of 850,000 tons for the chromite body. Although the boreholes completely penetrated the Gölalan ore body and encountered the country rock (see dotted drill holes in Fig. 16), it is now known that had they been drilled deeper at that time, they would have encountered at a greater depth the separate ore body discovered by the recent gravity and magnetic surveys.

When the gravity survey was started, all of the known chromite ore in the southeastern section of the Gölalan mass had been mined out, except for about 80,000 tons, which occurred at the bottom of an open cut in the form of a horizontal sheet with an average thickness of 4 meters (see Figs. 11 and 16).

The results of the recent gravity and magnetic surveys are given in Figures 11 to 16. Over the open cut in the remaining part of the Gölalan mass, the presence of a gravity high coinciding with a magnetic high (Figs. 15 and 16) warranted test drilling. The discovery hole, hole No. 25, which was the first drill hole recommended on the basis of these results, penetrated 34.5 meters of high-grade chromite, and thus established the existence of a separate ore body lying beneath the remainder of the Gölalan mass. Following the discovery, 26 additional exploration and development bore holes were drilled to delineate the ore body. Some of these holes are shown with solid lines in Figure 16. The drilling estab-

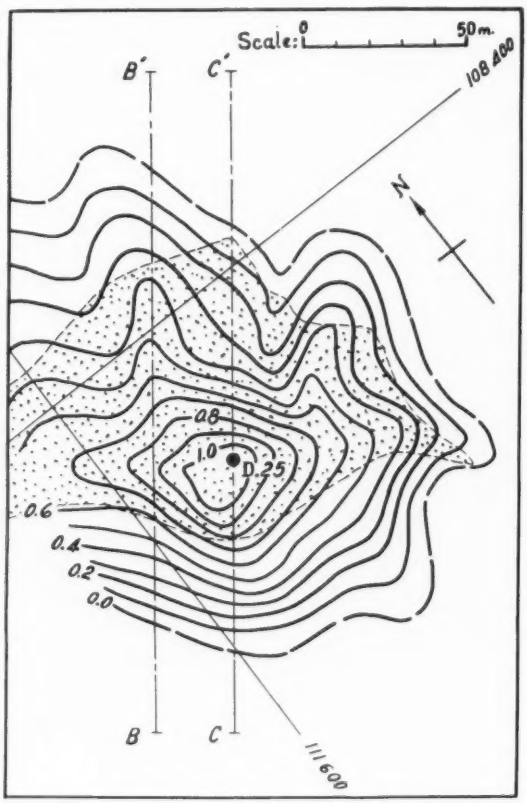

FIG. 13. Gölalan, gravity residual for $\sigma = 2.6$. Contour interval 0.1 mg.

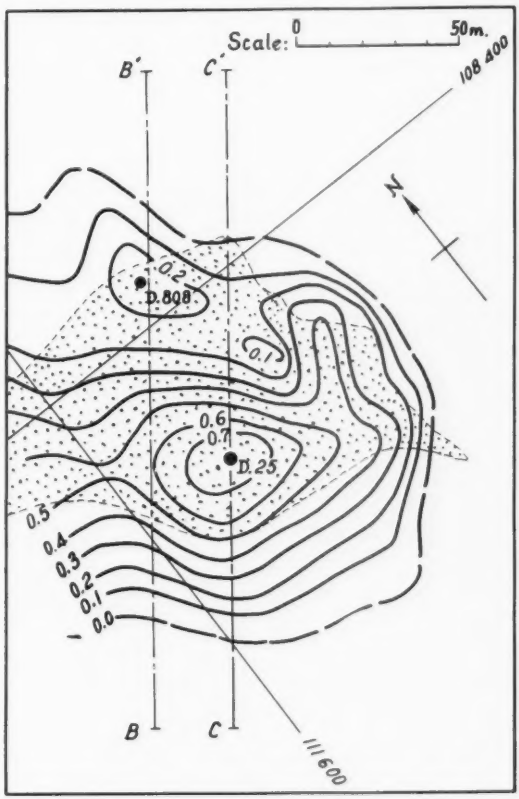

FIG. 14. Gölalan, gravity residual for $\sigma = 2.4$. Contour interval 0.1 mg.

lished a measured tonnage of 250,000 tons for the discovered ore body.

Prior to the recent drilling, estimates of the mass causing the gravity anomaly were (1) 370,000 tons using the *second derivative* gravity map (Fig. 12, with surface density, $\sigma = 2.6$) with $\rho_0 = 37$ m., $G_m = 13.5 \times 10^{-11}$ c.g.s. and the chart for a sphere (Fig. 2); (2) 417,000 tons by applying Hammer's (1945) method to the *residual* gravity map for a surface density, σ of 2.6 (Fig. 13); and (3) 245,000 tons, by applying Hammer's method to another *residual* gravity map for $\sigma = 2.4$ (Fig. 14), for which the terrain and elevation corrections for this density were recalculated. It was believed that the surface density was not lower than 2.4 and, consequently, the tonnage was not less then 245,000 tons, so that the true tonnage probably was between the estimated limits, namely between 245,000 and 417,000 tons. The average of the two estimates obtained by applying Hammer's method to the residual gravity maps, which is considered by the present writer more

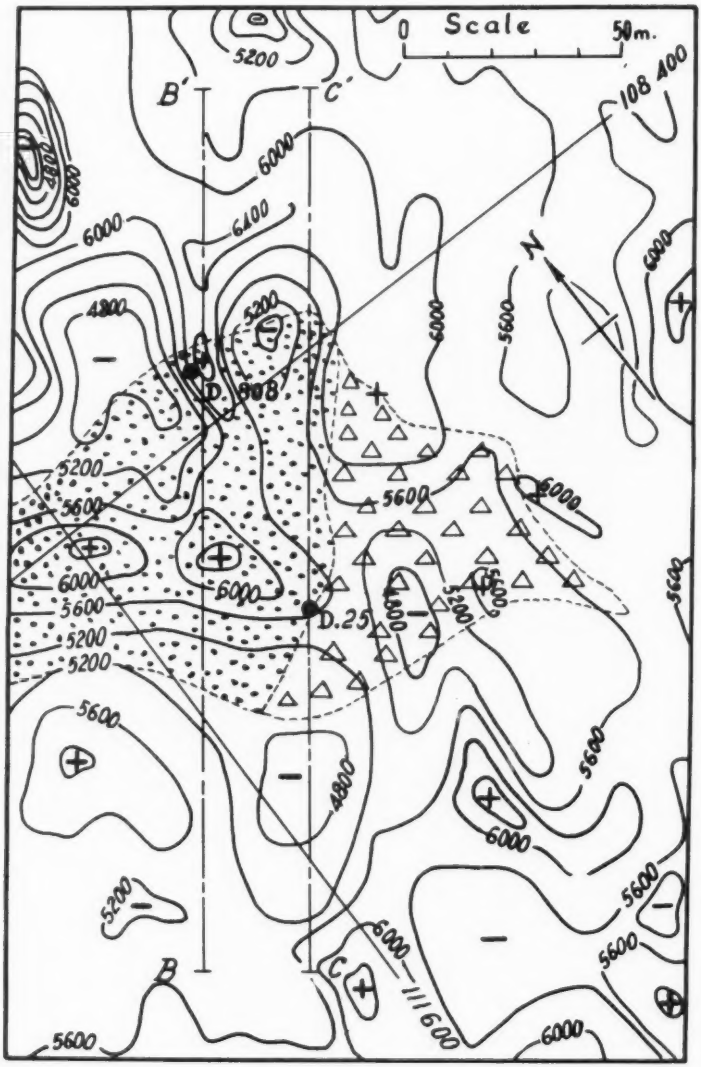

FIG. 15. Gölalan, magnetic vertical intensity in gammas, as of 1953.
Dotted area: massive chromite; triangles: broken chromite.

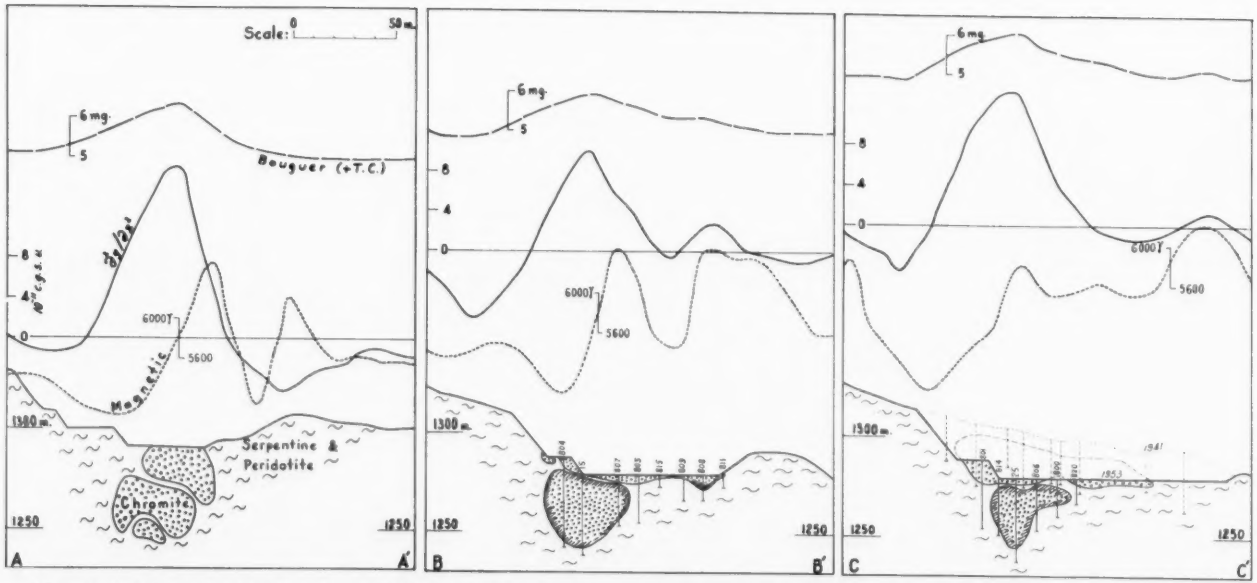

FIG. 16. Gölalan, gravity and magnetic profiles and geological sections, as of 1953. Drill holes shown with solid lines are subsequent to the recent geophysical work which led to the discovery of the chromite mass indicated with hachured areas. (The lower mass shown in Cross-sections *BB'* and *CC'* is separated from the one shown in Cross-section *AA'* by a distance of about 45 meters.)

accurate than the method using the second derivative gravity map, gives 331,000 tons, which agrees surprisingly well with the measured tonnage, when it is recalled that the mass determination also includes the 80,000 tons of the remaining part of the Gölalan mass. This agreement also suggests that a surface density of 2.5 should probably have been used throughout the survey, since it gave the best value in mass calculations.

Referring to Figures 15 and 16 (Profiles BB′ and CC′), a magnetic high was obtained over the newly discovered mass and apparently confirmed the existence of the chromite at depth, although the intensity must have been decreased due to the topographic feature here. In this area, massive chromite produced magnetic highs and broken chromite produced a mixture of magnetic lows and highs (see Figs. 9 and 15). Spurious lows could have been created by the presence of chromite walls on three sides, although stations close to them were disregarded.

A minor discovery of ore occurring as a downward bulge of the bottom contact near the margin of the Gölalan ore body was made by testing (hole No. 808, Figs. 14 and 15) a small gravity high that coincided with a small magnetic high. The bulge was missed by several small shafts that had been sunk in the area to outline more precisely the bottom of the Gölalan ore body. Hole No. 808 penetrated 7 meters of chromite, whereas the previously known thickness of ore was less than one meter.

In other areas within the Guleman concession, 18 gravity highs that warrant test drilling were found. Of these, only two coincided with magnetic highs. Five of these 18 anomalies were tested, but the results were similar to those in the Küdikan concession: Although no chromite ore was discovered, it was found that the gravity highs coincided with relatively dense masses, such as harzburgites, norites and red serpentine breccias.

ACKNOWLEDGMENTS

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GEOPHYSICS, VOL. XXI, NO. 2 (APRIL, 1956), PP. 455–469, 10 FIGS.

A TRI-POTENTIAL METHOD OF RESISTIVITY PROSPECTING*

E. W. CARPENTER† AND G. M. HABBERJAM‡

ABSTRACT

This paper describes a method whereby three resistances are measured for a four electrode configuration, and relations between these three resistances and their corresponding apparent resistivities are derived. The practical application of the resistance relation as a means of detecting observational and instrumental errors is indicated. The concept of apparent resistivity is examined and by means of examples it is shown that the apparent resistivity can take negative values. Finally, the possibility of using the triple resistivity method as a means of distinguishing between the effects of lateral and vertical resistivity changes on depth probes is discussed.

INTRODUCTION

The electrical resistivity method of geophysical prospecting basically involves passing a current I amps through the earth by means of two current electrodes C_1 and C_2 and measuring the *resulting* potential difference ΔV volts between two potential electrodes P_1 and P_2. In the following text the current will be considered to enter the earth at C_1 and leave at C_2, and the potential difference will be considered as positive when P_1 is at a higher potential than P_2. Let the distances between C_1 and P_1 , C_1 and P_2, C_2 and P_1, and C_2 and P_2 be X_{11}, X_{12}, X_{21} and X_{22} respectively. Then for the interpretation of experimental results a quantity ρ_a known as the apparent resistivity and defined by the equation

$$\rho_a = 2\pi RG \tag{1}$$

is conventionally derived, where R, the configuration resistance, and G, the configuration factor, are given by

$$R = \frac{\Delta V}{I} \tag{2}$$

and

$$G = \left[\frac{1}{X_{11}} + \frac{1}{X_{22}} - \frac{1}{X_{12}} - \frac{1}{X_{21}}\right]^{-1}. \tag{3}$$

In the widely used "expanding electrode probe" method of prospecting the relative dispositions of the four electrodes are kept constant whilst measurements are taken for increasing values of the electrode spacings. Many electrode configurations have been adopted by different authors (Heiland 1940, p. 709) but in

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this paper attention will be confined to the configuration shown below in Figure 1 where the electrodes are colinear with $X_{11}=X_{22}=r$ and $X_{12}=X_{21}=r+s$. The ratio r/s is held constant as the scale of the configuration is increased and the results are presented as graphs plotted of the apparent resistivity against s (or r). It may be noted in passing that the well-known Wenner electrode configuration is the particular case for which $r/s=1$.

At any site the value of the apparent resistivity obtained is governed by the positions of the electrodes and the distribution of resistivity within the earth, and it is the aim of the resistivity method to determine this latter distribution by examining how the apparent resistivity varies with the electrode spacings.

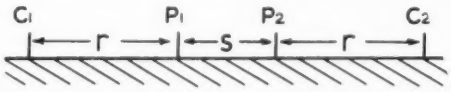

FIG. 1. The "Semi-symmetric" electrode configuration.

Unfortunately, the general problem of any resistivity distribution cannot be uniquely solved by such methods. Experience has shown, however, that certain simplifying assumptions can often be made about the types of resistivity distributions which occur in practice, and, within the limits imposed by these assumptions, valuable information concerning the relevant parameters can sometimes be obtained. Conspicuous amongst such simplifying assumptions are the two and three layer problems where the resistivity of the earth is a simple step function of depth, and it is for this type of problem that the expanding electrode probe method has had its most successful applications.

Many examples of apparent resistivity versus electrode spacing curves have been calculated and presented in the literature (see Koefoed 1955 for examples and bibliography) for problems where the resistivity is a function of depth only, and it should be especially noted that these take the form of smooth curves. In general, however, experimentally obtained curves do not have exactly the same regular shape as the theoretical curves, even when conditions suggest that good two or three layer problems exist. These divergences can sometimes be attributed to observational and instrumental errors but such an explanation will usually be inadequate and they must be attributed to the fact that the theoretically postulated conditions differ from the practical conditions.

In addition to the problems of dip and gradual lateral changes of resistivity, local resistivity changes are particularly prone to occur near to the surface and these surface variations tend to impart an irregular form to the field curve. Such lateral effects can be tested for by traversing along the line of the probe using a constant electrode spacing or by running probe lines in different azimuths keeping their centre points fixed. Unfortunately these methods are very time consuming and are rarely employed in the field. As a possible alternative to the above procedures, a method has recently been described by one of us (Carpenter 1955) whereby three resistances are measured for each separate electrode spacing, and

in this paper it is proposed to develop the triple resistance method for the configuration shown in Figure 1 rather than for the more specialised Wenner configuration for which $r=s$.

Considering the configuration of Figure 1, let the electrodes be numbered 1, 2, 3 and 4 from left to right, then there are 24 ways in which C_1, C_2, P_1 and P_2 can be arranged amongst them. For any particular arrangement interchanging the subscripts of either the potential or current electrodes separately alters the sign but not the magnitude of both the resistance R and the configuration factor G, but changing the subscripts of both the potential and current electrodes together has no effect on either R or G. Therefore, ignoring the subscripts for the time being, it is only necessary to consider the six ways in which two potential and two current electrodes can be distributed amongst any four electrode configuration. Now by a generalised form of Helmholtz's Reciprocal Theorem (Searle 1910), interchange of current and potential electrodes does not affect the value of the measured resistance, and therefore there can only be three basically different resistances for any four electrode configuration, although, as described above, their signs will depend upon the way in which the directions of the current and potential difference are defined, i.e. the way in which the subscripts are arranged. Also, from equation 3, an interchange of current and potential electrodes does not affect either the sign or magnitude of G, and therefore there are only three apparent resistivities for any four electrode configuration.

For the resistances and apparent resistivities the following nomenclature has been adopted:

(i) The α configuration, either two current or two potential electrodes adjacent, i.e. *CPPC* or *PCCP*, with resistance $(\pm)R^{\alpha}$ and apparent resistivity $\rho_a{}^{\alpha}$.

(ii) The β configuration, both current and both potential electrodes adjacent, i.e. *CCPP* or *PPCC*, with resistance $(\pm)R^{\beta}$ and apparent resistivity $\rho_a{}^{\beta}$.

(iii) The γ configuration, neither potential nor current electrodes adjacent, i.e. *CPCP* or *PCPC*, with resistance $(\pm)R^{\gamma}$ and apparent resistivity $\rho_a{}^{\gamma}$.

These definitions are summarised in Table I, which also gives the appropriate values of G in terms of r and s. The signs of R and G can be either positive or nega-

TABLE I

Electrode Configuration $1\leftarrow r\rightarrow 2\leftarrow s\rightarrow 3\leftarrow r\rightarrow 4$				Resistance R	Configuration Factor G	Apparent Resistivity
C	*P*	*P*	*C*	$(\pm)R^{\alpha}$	$(\pm)\frac{r(r+s)}{2s}$	$\rho_a{}^{\alpha}$
P	*C*	*C*	*P*			
C	*C*	*P*	*P*	$(\pm)R^{\beta}$	$(\pm)\frac{s(2r+s)(r+s)}{2r^2}$	$\rho_a{}^{\beta}$
P	*P*	*C*	*C*			
C	*P*	*C*	*P*	$(\pm)R^{\gamma}$	$(\pm)\frac{rs(2r+s)}{2(sr+s^2-r^2)}$	$\rho_a{}^{\gamma}$
P	*C*	*P*	*C*			

tive, depending upon the way in which the subscripts are arranged, but the values of ρ_a are independent of the subscripts, although, as will be shown later, ρ_a can take negative values.

A number of interesting relations can now be derived between the resistances and apparent resistivities. To remove the ambiguity of the signs to be associated with the resistances and configuration factors the following specific set of configurations will be considered: $C_1\ P_1\ P_2\ C_2$, $C_1\ C_2\ P_2\ P_1$ and $C_1\ P_1\ C_2\ P_2$.

Let ϕ_{jk} be the potential at an electrode j due to unit current entering the earth at an electrode k. Then for the configuration $C_1\ P_1\ P_2\ C_2$

$$R^\alpha = \phi_{21} - \phi_{24} + \phi_{34} - \phi_{31}, \tag{4}$$

for the configuration $C_1\ C_2\ P_2\ P_1$

$$R^\beta = \phi_{41} - \phi_{42} + \phi_{32} - \phi_{31}, \tag{5}$$

and for the configuration $C_1\ P_1\ C_2\ P_2$

$$R^\gamma = \phi_{21} - \phi_{23} + \phi_{43} - \phi_{41}. \tag{6}$$

Since $\phi_{jk} = \phi_{kj}$, from the above three equations

$$R^\alpha = R^\beta + R^\gamma. \tag{7}$$

This relation has been specifically derived for the above particular set of electrode configurations, but similar relations can readily be derived for any other set of configurations and these can only differ from equation 7, if at all, by having the sign of one of the resistances changed.

In the remainder of this paper, however, the three resistances employed will be those defined by equations 4, 5 and 6.

Writing $r/s = u$, the expressions for the apparent resistivities become

$$\rho_a{}^\alpha = u(u+1)s\pi R^\alpha, \tag{8}$$

$$\rho_a{}^\beta = \frac{(2u+1)(u+1)s\pi R^\beta}{u^2}, \tag{9}$$

and

$$\rho_a{}^\gamma = \frac{u(2u+1)s\pi R^\gamma}{u+1-u^2}, \tag{10}$$

so that substituting these relations in equation 7,

$$(2u+1)\rho_a{}^\alpha = u^3\rho_a{}^\beta + (2u+1-u^3)\rho_a{}^\gamma \tag{11}$$

whence

$$\frac{\rho_a{}^\gamma - \rho_a{}^\alpha}{\rho_a{}^\gamma - \rho_a{}^\beta} = \frac{u^3}{2u+1} = M \text{ (say)}. \tag{12}$$

Since u is, by definition, always positive, M is also always positive so that if the three apparent resistivities are not equal $\rho_a{}^\gamma$ is always either the greatest or the least. For values of M less than unity $\rho_a{}^\alpha$ is the middle resistivity, but for values of M greater than unity $\rho_a{}^\beta$ is the middle resistivity. Figure 2 shows the values of M plotted as a function of u.

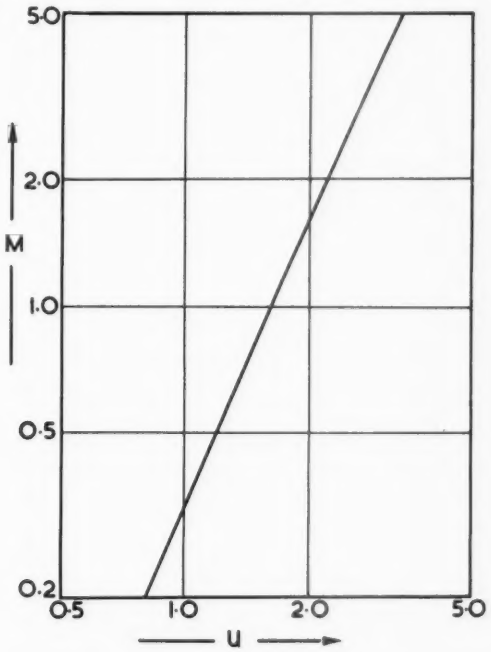

FIG. 2. Graph of M as a function of u.

The particular case of $M=1$ which occurs when

$$u = \frac{1+\sqrt{5}}{2} = 1.62 \text{ (approx.)} \tag{13}$$

is of interest since $\rho_a{}^\beta = \rho_a{}^\alpha$. Also, for homogeneous ground bounded by a plane surface, $R^\gamma = 0$, so that divergences from such conditions could be readily recognised in practice if the measured resistance R^γ was not equal to zero.

For values of u greater than that given by equation 13 the configuration factor for the configuration $C_1\ P_1\ C_2\ P_2$ becomes negative. This means that for homogeneous ground bounded by a plane surface the potential of P_2 is greater than the potential of P_1, so that R^γ would be negative also. A rather more interesting

example where the configuration factor and resistance have opposite signs will be referred to in a later section of this paper.

ERRORS IN THE RESISTANCE MEASUREMENTS

Let $R(m)$ and $R(t)$ be the measured and true resistances respectively, then a relation of the form

$$R(m) = R(t) + \epsilon \tag{14}$$

will generally hold between them, where ϵ is a small quantity. From equation 7

$$R^{\alpha}(m) - R^{\beta}(m) - R^{\gamma}(m) = \epsilon^{\alpha} - \epsilon^{\beta} - \epsilon^{\gamma} = E \text{ (say)}. \tag{15}$$

If the quantity on the right hand side of the above equation is not equal to zero it will indicate that errors are occurring in the resistance readings. Such errors may be of several types, for example, personal errors, errors due to incorrect calibration of the instrument, etc. An examination of the values of E should readily indicate the grosser personal errors, and a whole series of values may provide information about the accuracy of the instrument, particularly errors in its zero setting which make each reading either too large or too small by a constant amount. Application of the "E" test is not entirely satisfactory however, for apart from E having a fortuitous value of zero, each individual error may be linearly proportional to the true resistance which would also give E a value of zero. This latter type of error is simply equivalent to an error in the units employed and will only affect the absolute magnitudes of the interpreted resistivities. It will not affect the interpretation in any other way and hence cannot be regarded as a serious objection to the test.

APPARENT RESISTIVITY

The apparent resistivity as defined by equation 1 has sometimes been referred to as the mean resistivity, the implication being that it is some type of weighted mean of the true resistivities of the underlying strata. This concept has proved

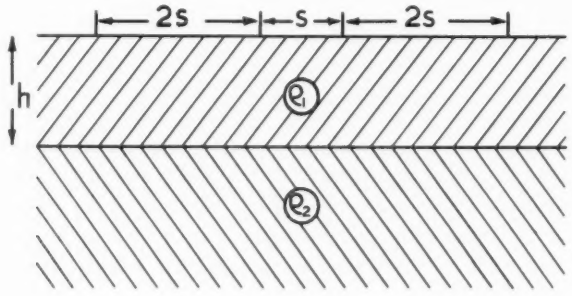

FIG. 3. Two-layer case with configuration defined by $r/s = 2$.

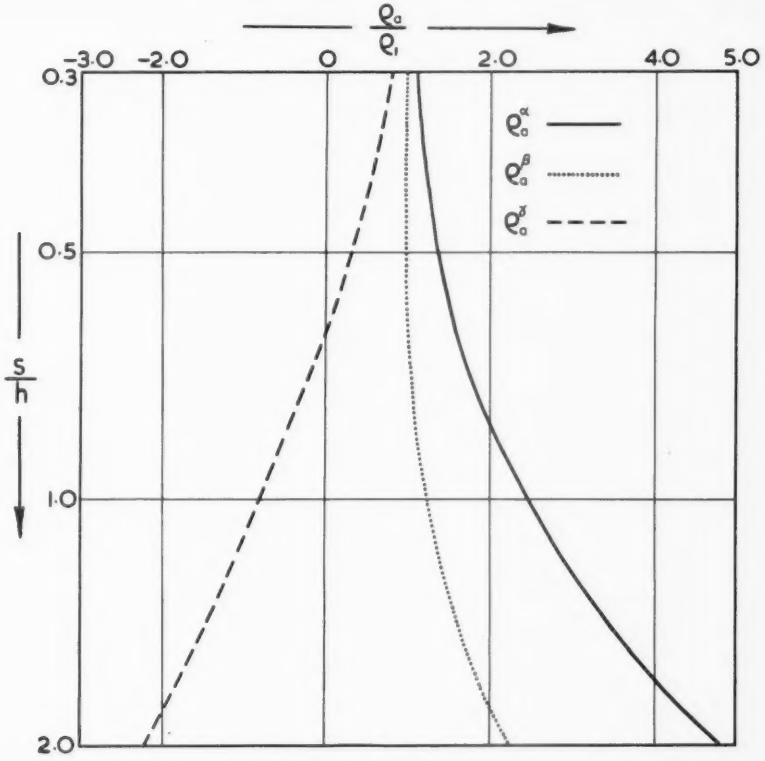

FIG. 4. Theoretical apparent resistivity curves for the two-layer case where the lower medium is a perfect insulator, using the configuration defined by $r/s = 2$.

useful in many simple problems, but its limitations are well illustrated by the following interesting example.

Consider the two layer problem of a uniform homogeneous and isotropic medium of resistivity ρ_1 and thickness h overlying a semi-infinite medium of infinite resistivity, the interfaces being plane parallel and infinite, and suppose that such a case is being investigated using an expanding electrode probe for which r/s is kept constant at a value of two, see Figure 3. Such a problem can readily be treated theoretically by means of tables published by Roman (1931), and the results are shown in Figure 4 as $\rho_a{}^\alpha/\rho_1$, $\rho_a{}^\beta/\rho_1$ and $\rho_a{}^\gamma/\rho_1$ plotted against s/h. It will be seen that as s increases $\rho_a{}^\alpha$ increases in the usual manner associated with the Wenner configuration. After a slight fall *below the value of* ρ_1, $\rho_a{}^\beta$ also increases with s. On the other hand, $\rho_a{}^\gamma$ decreases as s increases, and for values of s greater than $0.612h$ it actually becomes *negative*. For large values of s/h it can be shown

that the values of the three apparent resistivities asymptotically approach those given by the equations

$$\rho_a{}^{\alpha} = 3\rho_1 \frac{s}{h} \log_e \left(\frac{9}{4}\right), \tag{16}$$

$$\rho_a{}^{\beta} = \frac{15}{8} \rho_1 \frac{s}{h} \log_e \left(\frac{9}{5}\right), \tag{17}$$

and

$$\rho_a{}^{\gamma} = -\ 5\rho_1 \frac{s}{h} \log_e \left(\frac{5}{4}\right). \tag{18}$$

From these asymptotic expressions for large values of s/h,

$$\frac{\rho_a{}^{\gamma} - \rho_a{}^{\alpha}}{\rho_a{}^{\gamma} - \rho_a{}^{\beta}} = \frac{-\log_e \left(\frac{5}{4}\right) - \frac{3}{5} \log_e \left(\frac{9}{4}\right)}{-\log_e \left(\frac{5}{4}\right) - \frac{3}{8} \log_e \left(\frac{9}{5}\right)} \tag{19}$$

$$= 1{\cdot}6$$

which is the value of M for the configuration $r/s = 2$.

That the apparent resistivity can sometimes take negative values is quite a surprising result and affords an excellent illustration of the artificiality of the apparent resistivity concept and of the dangers of regarding it as a weighted mean of the true resistivities.

For more practical cases where the resistivity of the lower medium, ρ_2, is greater than ρ_1 but not infinite, $\rho_a{}^{\gamma}$ has a minimum value and for large values of s/h approaches the value of ρ_2. Only for values of ρ_2 greater than about $6\rho_1$ does the minimum value of $\rho_a{}^{\gamma}$ become negative.

To simulate a two layer problem for which $\rho_2 = \infty$ a glass sheet was suspended horizontally in a brine filled tank at a depth of 5.7 cms. Using this arrangement a probe was carried out using the configuration $r/s = 2$, the three resistances being measured for values of s between 3 and 13 cms at intervals of 1 cm. In addition to the effects of the sides of the tank, lateral effects due to current being able to flow beneath the sheet would be expected. The actual results are shown in Figure 5 together with the theoretical curves for $\rho_2 = \infty$ and $h = 5.7$ cms. For small values of s there is good agreement between the experimental and theoretical values, but as s increases there is a progressive divergence between them, the experimental values of $\rho_a{}^{\beta}$ and $\rho_a{}^{\gamma}$ increasing and those of $\rho_a{}^{\alpha}$ decreasing with respect to the appropriate theoretical values. These divergences must be attributed to the lateral effects mentioned above, but it is interesting to note that $\rho_a{}^{\gamma}$ does become negative.

The actual experimentally determined values are shown in Table II, together with the values of $R^{\alpha}/(R^{\beta}+R^{\gamma})$ which, within the limits of experimental error,

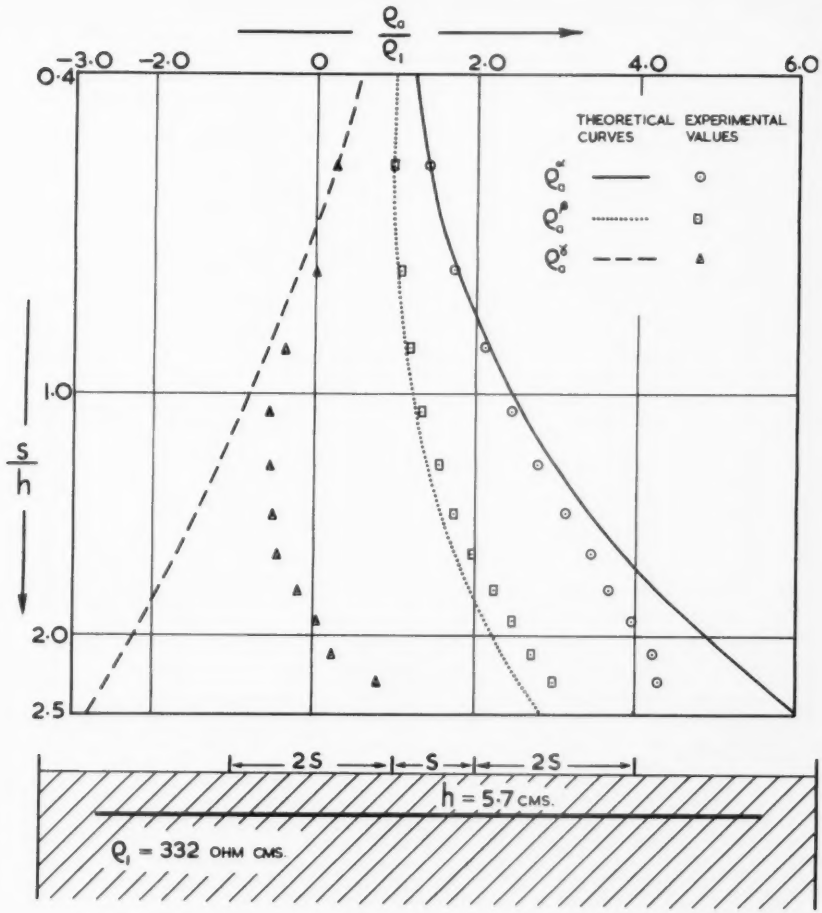

FIG. 5. Results of a small-scale model experiment using a glass sheet suspended in a tank of brine.

agree with the theoretical value of unity. It will be noted that since R^γ twice changes sign, little could have been gained by using the configuration $C_1\ P_2\ C_2\ P_1$ and making G positive rather than using $C_1\ P_1\ C_2\ P_2$ with G negative.

THE EFFECTS OF LATERAL RESISTIVITY VARIATIONS ON DEPTH PROBES

The interpretation of expanding electrode probes is usually performed by fitting the observed curve to one of a set of theoretical curves calculated for specific problems. Such a method can be used to interpret triple apparent resistivity curves with the advantage that the three observed curves have to be fitted simul-

TABLE II

MODEL TANK EXPERIMENT USING THE CONFIGURATION $r/s=2$ (SEE FIG. 5)
Resistivity of brine = 332 ohm cms

$C_1\ P_1\ P_2\ C_2$ $\qquad \rho_a{}^{\alpha}=6\pi s R^{\alpha}$

$C_1\ C_2\ P_2\ P_1$ $\qquad \rho_a{}^{\beta}=\frac{15}{4}\pi s R^{\beta}$

$C_1\ P_1\ C_2\ P_2$ $\qquad \rho_a{}^{\gamma}=-10\pi s R^{\gamma}$

s cms.	R^{α} ohms	R^{β} ohms	R^{γ} ohms	$\frac{R^{\alpha}}{R^{\beta}+R^{\gamma}}$	$\rho_a{}^{\alpha}$ ohm cms	$\rho_a{}^{\beta}$ ohm cms	$\rho_a{}^{\gamma}$ ohm cms
3	8.20	9.20	−1.01	1.001	464	325	95
4	7.48	7.57	−0.090	1.000	564	357	11
5	7.38	6.58	0.768	1.004	696	388	−121
6	7.18	6.26	0.900	1.003	812	443	−170
7	6.99	6.18	0.798	1.002	922	510	−175
8	6.82	6.13	0.690	1.000	1,028	577	−173
9	6.74	6.19	0.528	1.003	1,143	656	−149
10	6.46	6.26	0.202	1.000	1,218	737	− 63
11	6.30	6.34	−0.031	0.999	1,307	822	11
12	6.18	6.38	−0.196	1.000	1,398	902	74
13	5.80	6.50	−0.682	0.997	1,421	995	279

taneously on a set of three calculated curves. Most of the theoretical curves available in the literature have been calculated specifically for the α form of the Wenner configuration, but if this configuration is adopted for the triple resistivity method comparatively little effort is required to calculate the additional β and γ curves. By using a series summation method of the type given by West (1940) either the β or γ curves can be readily calculated from the appropriate α curve whilst the remaining curve can be obtained by substituting in equation 11, which for the Wenner configuration reduces to the simple form

$$3\rho_a{}^{\alpha} = \rho_a{}^{\beta} + 2\rho_a{}^{\gamma}. \tag{20}$$

Whilst such series usually converge quite rapidly the method can be considerably abbreviated by introducing a further relation.

Consider the case of a semi-infinite medium, bounded by a plane surface, whose resistivity is a function of depth only, and let $\phi(s)$ be the potential at an electrode on the surface due to unit current entering the surface of the medium at an electrode a distance s away. Such a problem is characterised by the fact that $\phi(s)$ is independent of the actual positions of the two electrodes on the surface and thus for the Wenner configuration

$$\rho_a{}^{\alpha}(s) = 2\pi s\left[2\phi(s) - 2\phi(2s)\right] \tag{21}$$

and

$$\rho_a{}^{\gamma}(s) = 3\pi s\left[\phi(s) - \phi(3s)\right] \tag{22}$$

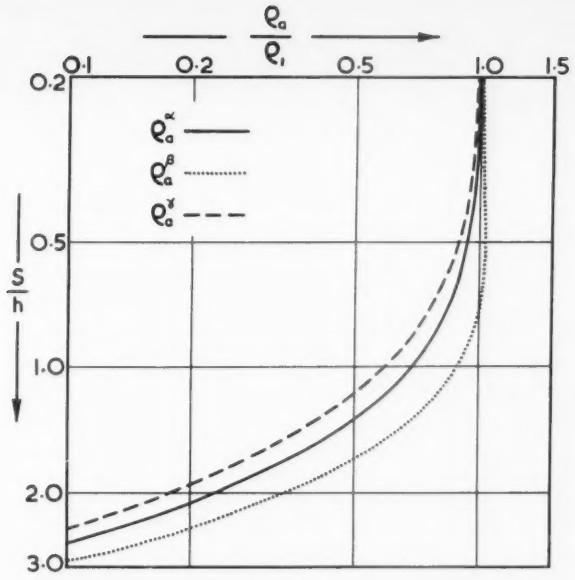

FIG. 6. Two-layer curves for the case where the lower medium is a perfect conductor using a Wenner electrode configuration for which $r/s = 1$.

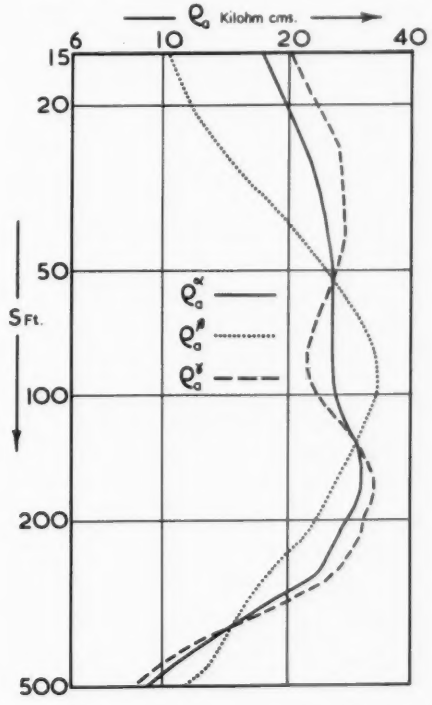

FIG. 7. Triple apparent resistivity curves obtained in the field using a Wenner electrode configuration.

where $\rho_a(s)$ is the apparent resistivity for a Wenner configuration with inter-electrode spacings s. Similar expressions for $\rho_a(ns)$ can readily be derived by substituting ns for s, whence

$$4\rho_a^{\gamma}(s) - 3\rho_a^{\alpha}(s) - 2\rho_a^{\gamma}(2s) + \rho_a^{\alpha}(3s) = 0 \tag{23}$$

or

$$\rho_a^{\gamma}(2s) = 2\rho_a^{\gamma}(s) + \tfrac{1}{2}[\rho_a^{\alpha}(3s) - 3\rho_a^{\alpha}(s)]. \tag{24}$$

This relation will considerably reduce the work involved in computing a γ curve from an α curve, for once a few points have been computed by series summation more may quickly be added by substitution in equation 24.

Examples of a number of triple apparent resistivity curves for simple depth problems have been given in a previous paper (Carpenter 1955) and a further example for a two layer problem using a Wenner configuration is shown in Figure 6. It has been found that for problems where the resistivity is a function of depth

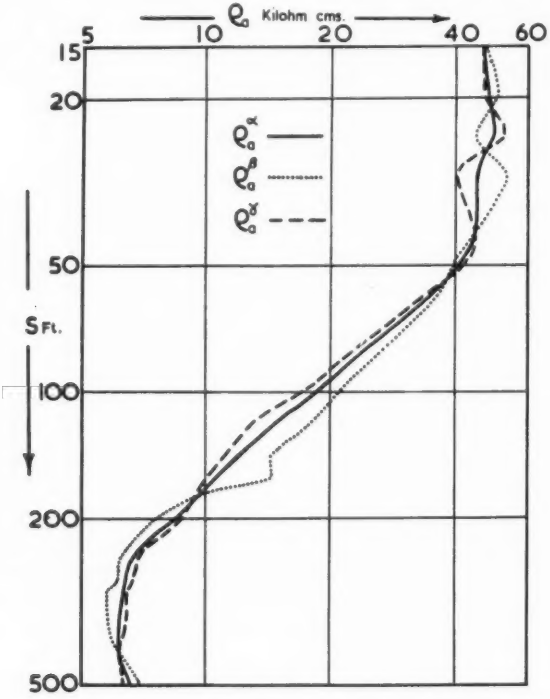

FIG. 8. Triple apparent resistivity curves obtained in the field using a Wenner electrode configuration.

only, the α, β, and γ curves for the Wenner configuration are smooth and have the same general trends, although there are some slight exceptions such as that illustrated in Figure 6 where the β curve has a rather anomolous appearance for small values of s. When the electrode line crosses a lateral resistivity discontinuity however, the curves often show sharp, and sometimes discontinuous, changes of apparent resistivity, further characterised by either a divergence or convergence of the curves, see Figures 7 and 8 which are experimental field curves.

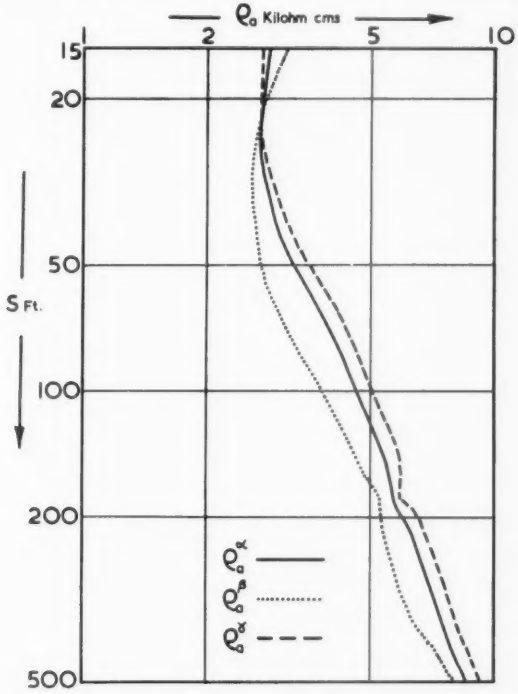

FIG. 9. Triple apparent resistivity curves obtained in the field using a Wenner electrode configuration.

An example of a single local surface effect is shown in Figure 9 for an experimental Wenner configuration probe where one of the outer electrodes crossed a stream at an electrode spacing of about 180 ft. The effect of the stream is clearly shown as a local convergence of the apparent resistivity curves.

A rather more objective test for lateral effects can be applied by utilising equation 23. Writing this equation in the form

$$4\rho_a^{\gamma}(s) - 3\rho_a^{\alpha}(s) - 2\rho_a^{\gamma}(2s) + \rho_a^{\alpha}(3s) = A(s) \qquad (25)$$

where the apparent resistivities are now observed quantities, departures of the value of $A(s)$ from zero must indicate departures of the actual resistivity distribution from one which is a function of depth only, provided of course that the data used are free from any observational and instrumental errors.

In Figure 10 a graph is shown of $A(s)$ against s for the curves given in Figure

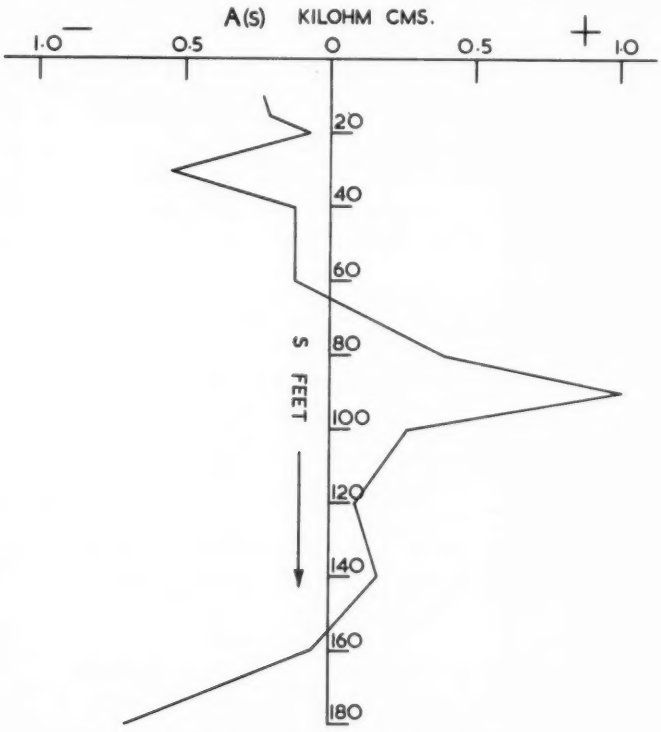

FIG. 10. Residual curve for the results shown in Figure 9.

9. Referring back to the latter figure the apparent resistivities for $s = 180$ ft. are suspect and can be expected to give finite values of $A(180)$, $A(90)$ and, to a lesser extent, $A(60)$ if in fact lateral effects are present. The graph of $A(s)$ v. s does in fact show anomalies at $A(180)$ and $A(90)$ although, because of the general scatter of values, $A(60)$ does not differ appreciably from unity.

Whilst the triple assemblage of curves is useful as a rapid means of identifying local anomalies, the "residual" curve of $A(s)$ v. s may be considered as an indication of how closely the actual conditions approximate to a resistivity distribution which is a function of depth only. It may be expected that accumulated

experience of such residual curves will enable a direct assessment to be made of the extent to which a depth interpretation should be attempted. It should be stressed, however, that finite values of $A(s)$ only indicate that the observed quantities cannot be reconciled with a resistivity distribution which is a function of depth only, whilst a zero value of $A(s)$ does not necessarily imply that such a resistivity distribution does in fact exist. In order that residual curves for different probes can be compared directly, it will probably be necessary to use a ratio of the type $A(s)/\rho_a{}^{\alpha}(s)$ rather than simply the quantity $A(s)$. Alternatively it may prove useful to use a ratio of the type

$$[4\rho_a{}^{\gamma}(s) + \rho_a{}^{\alpha}(3s)]/[3\rho_a{}^{\alpha}(s) + 2\rho_a{}^{\gamma}(2s)]$$

where lateral effects are indicated when its value is not equal to unity. There is thus considerable scope for further investigation and it is hoped that this preliminary work may lead to the further elucidation of some resistivity problems.

ACKNOWLEDGMENTS

The authors wish to express their sincere thanks to Professor John T. Whetton, Head of the Mining Department, Leeds University, for his keen interest and advice during the course of the work.

Acknowledgment is also made to the Department of Scientific and Industrial Research who awarded one of us (E. W. C.) a maintenance grant, and also to the Scientific Department, National Coal Board, for a grant in aid of this research.

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GEOPHYSICS, VOL. XXI, NO. 2 (APRIL, 1956), PP. 470-478, 6 FIGS.

THE DETERMINATION OF THE LONG DIMENSION OF CONDUCTING ORE BODIES*

A. R. CLARK†

ABSTRACT

A solution of Laplace's equation in prolate spheroidal coordinates has been used to show that the resistivity profile obtained, when one current electrode is in the conducting body, may be used to obtain an estimate of the extent of the body along the long axis. The theoretical and experimental curves from a dipping conductor are compared.

INTRODUCTION

In mining exploration, after an ore body has been discovered, by geophysical means, by surface prospecting, or by diamond drilling, it becomes important to obtain some indication of the long dimension of the body, especially when the long axis dips into the earth.

One method of measuring earth resistivities is carried out by introducing an alternating current of I amperes into the earth through a point electrode placed either on the earth's surface or in a diamond drill hole and a second electrode placed far enough away so that it may be assumed to be at infinity. The potential difference, V, between points R_1 and R_2 length units from the first point electrode is measured by a sensitive, stable vacuum tube voltmeter and the apparent average resistivities, ρ, are calculated from—

$$\rho = 4\pi \frac{V}{I}\left(\frac{R_1R_2}{R_2 - R_1}\right). \tag{1}$$

As R_1, R_2 are increased, keeping R_2-R_1 constant, the apparent average resistivities at increasing distances from the current electrode are obtained. The values so calculated should be constant if the rock is homogeneous. In practice it is found that these values actually increase continuously with increasing distance from the current electrode. A typical curve obtained in a drill hole in reasonably homogeneous rhyolite is shown in Fig. 1.

The data from which the curve was drawn was obtained in a vertical diamond drill hole 1,500 feet long, at the Aldermac Mine, Arntfield, Quebec. The hole was collared on a level which was approximately 1,300 feet below the surface. One current electrode was at the bottom of the hole. Four other electrodes on the earth's surface, equally spaced on the circumference of a circle of one-half mile radius were connected in parallel and served as the second electrode. The resistance to ground of each surface electrode was adjusted to the same value.

Tests on core samples from extensive diamond drilling in all directions around the hole indicated that the rock varied little in resistivity.

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The unexpected behaviour of the calculated values is probably due to the current distribution being different from that assumed in deriving the expression used to calculate resistivities. In the derivation of the formula the current is assumed to flow radially from the electrode. In actual measurements the conditions necessary for this type of current flow cannot be realized. The actual flow is not radial, causing a distortion of the equipotential surfaces about the electrode and a change from the expected potential gradient along the hole.

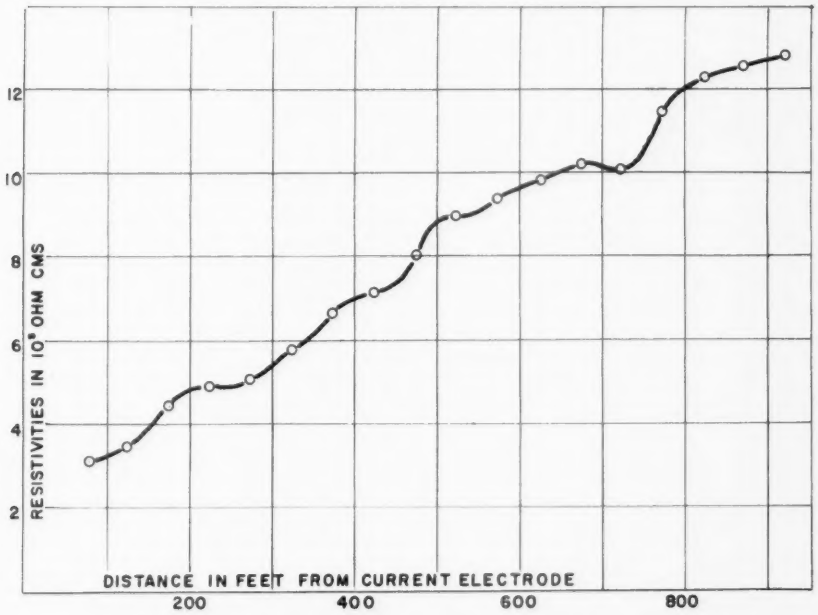

FIG. 1. Resistivity profile from measurements in a drill hole in rhyolite.

When a conducting ore body is being investigated, and one point electrode is placed in the body, the apparent average resistivities calculated from potentials measured outside the ore body either remain quite constant or increase slowly for a given distance. Beyond this point the increase becomes much more rapid. It has been noted in every investigation that the position where the sudden increase occurs depends on the magnitude of the long dimension of the conductor.

The author and Salt (1951) have shown the results of investigations on a conducting ore body whose dimensions were well known. The resistivity profiles exhibited low values until the distance of the potential electrodes from the current electrode was equal to the distance the ore body extended from the drill intersection. Beyond this point the calculated resistivity values increased rapidly.

For the purpose of theoretical considerations, sheet-like ore bodies, such as veins or bedded deposits may be represented by oblate spheroids, while long lens-like ore bodies, such as some replacement deposits, are best approximated by prolate spheroids.

Seigel (1952) has presented a method to determine the extent of the tabular type ore body from electrical measurements in a diamond drill hole. The method presented dealt only with the case where the drill hole intersected an ore body near its short axis and was perpendicular to the plane of the body.

Many of the replacement type ore bodies found in Canada are not tabular and are best represented by prolate spheroids with the long axis vertical or steeply dipping. It is the purpose of this paper to investigate the theoretical resistivity profiles from conducting prolate spheroids, with the long axis vertical and with the long axis dipping in order to show how the magnitude of the long dimension of an ore body may be estimated from the shape of the resistivity profile.

OUTLINE OF THE THEORY

In solving the problem in potential theory which arises when current is introduced into a conducting ore body it is convenient to choose a coordinate system such that its boundary may be represented by a constant value of one of the coordinates.

Most ore bodies are very irregular in shape. However, lens-like bodies which are much longer in one direction than the other two may be approximated by ellipsoids whose axes are three different lengths. The formal solution of Laplace's equation in ellipsoidal coordinates and conversion of the mathematics into useful curves is made very difficult by the relatively small amount of information available concerning Lamé functions. A further approximation to prolate spheroids leads to a series solution in Legendre polynomials which are extensively tabulated.

The prolate spheroidal coordinate system with the Z-axis vertical (Smythe, 1950, p. 158–169) may be used to investigate a lens-like ore body whose long dimension is at right angles to a diamond drill hole, or with the Z-axis dipping it may be used to investigate a body whose long dimension makes an angle with a drill hole or drift.

Consider a spheroidal ore body whose boundary is given by $\eta=\eta_1$, in prolate spheroidal coordinates. Let ρ_0 be the resistivity of the ore and ρ_r that of the surrounding rock. If the current electrode is situated at a point which is on the Z-axis, the potential is symmetrical about the Z-axis. If Laplace's equation in prolate spheroidal coordinates is set up and a solution obtained subject to the boundary conditions that the normal flow of current across the boundary of the ore body is continuous and that the potential at $\eta=\eta_1$ is the same for both media, then for the case of the current electrode in the ore, the potential at points outside the conducting body is given by

$$V = \frac{\rho_0 I}{4\pi}\left[\frac{1}{R} + \frac{\rho_0 - \rho_r}{c}\sum_{n=0}^{\infty}(2n+1)\frac{K_n(\eta_1)P_n(\xi_0)P_n(\eta_0)P_n(\xi)Q_n(\eta)}{\rho_r L_n(\eta_1) - \rho_0 K_n(\eta_1)}\right] \qquad (2)$$

where $P_n(x)$, $Q_n(x)$ are the Legendre functions of the first and second kinds, respectively. R is the distance from current source to the point where the potential is to be calculated, I is the current strength,

$$K_n(x) = P_n(x)/Q_n(x),$$

and

$$L_n(x) = P_n'(x)/Q_n'(x).$$

Where b and a are the semimajor and semiminor axes of the ellipsoid whose surface coincides with

$$\eta = \eta_1, \qquad c = \sqrt{b^2 - a^2}.$$

The more general formula (Cook and Van Nostrand, 1954), which was published just after the above expressions had been independently derived, reduces to the same formula when $m = 0$.

THEORETICAL RESISTIVITY CURVES FROM SPHEROIDAL ORE BODIES

Using the tabulated values of $P_n(x)$ and $Q_n(x)$ (Lowan, 1945), theoretical potential curves for a prolate spheroidal conductor of given size and resistivity contrast with the surrounding rock may be obtained. This curve in turn may be used to obtain the potential difference between points R_1 and R_2 units from the current electrode and the theoretical apparent average resistivities may be calculated for increasing values of R_1 and R_2 (formula 1). The results may then be plotted in the form of a resistivity profile. Figures 2, 3 and 4 show three such profiles. In each case the boundary of the body was taken as $\eta_1 = 1.1$, c was $b/1.1$, and $\rho_r/\rho_0 = 10$. The values of R_1 and R_2 were chosen to keep $R_2 - R_1$ constant.

Fig. 2 shows the type of resistivity profile to be expected from measurements in a drill hole or drift, intersecting an ore body close to the end and perpendicular to the strike. It will also approximate the results obtained on surface from a vertical body. In this case, there will of course be distortion of the expected potential pattern because of the conductivity discontinuity at the surface. The magnitude of the error introduced by neglecting the surface effect is difficult to determine. Webb (1931) has derived solutions for a buried sphere and spheroid. No curves were given, in the case of the spheroid, showing the effect of the omission of the surface distortion. The magnitude depends on the relation between the lateral dimension of the ore body and the distance from the surface to the top of the body. For practical purposes the errors do not appear to be any more serious than those introduced by the assumption that the body is spheroidal in shape. It may be

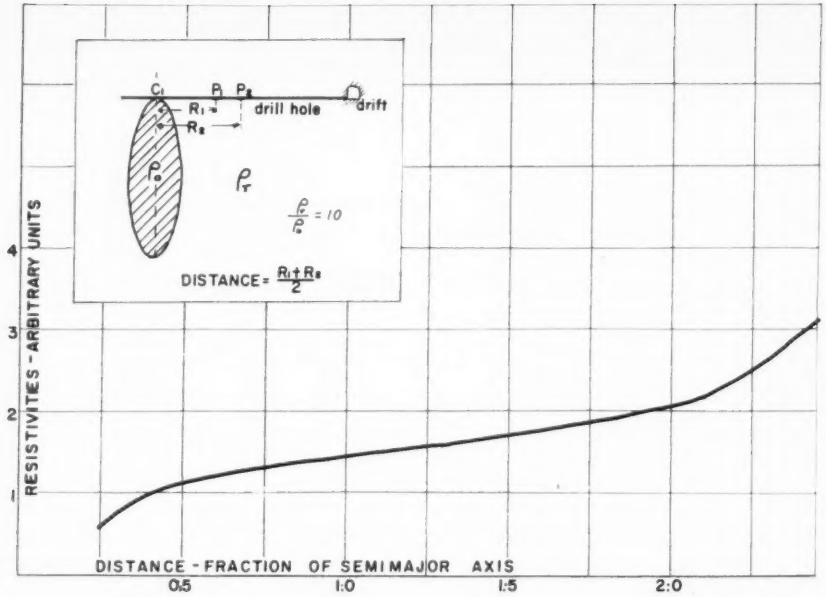

FIG. 2. Theoretical resistivity profile from a vertical prolate spheroidal conductor with the current electrode at end of the spheroid.

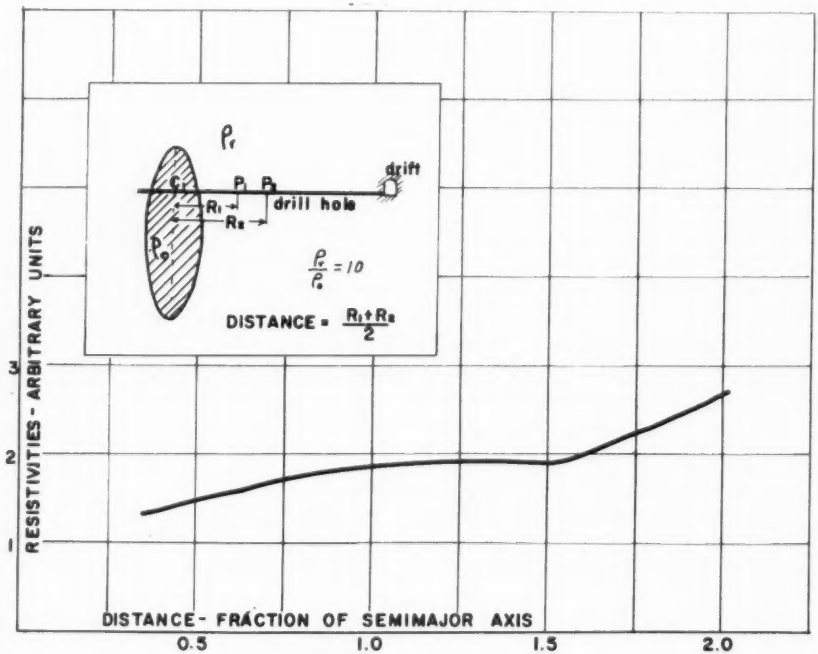

FIG. 3. Theoretical resistivity profile from a vertical prolate spheroidal conductor with the current electrode between the centre and end of the spheroid.

noted that the calculated resistivity values start to increase rapidly when the distance from the current electrode is equal to the distance the body extends from the drill hole or drift intersection.

If a drill hole or drift intersects a conducting body at right angles, but between its centre and end, a resistivity profile similar to Fig. 3 should be obtained. As before, the sharper increase in the resistivity values occurs at a distance from

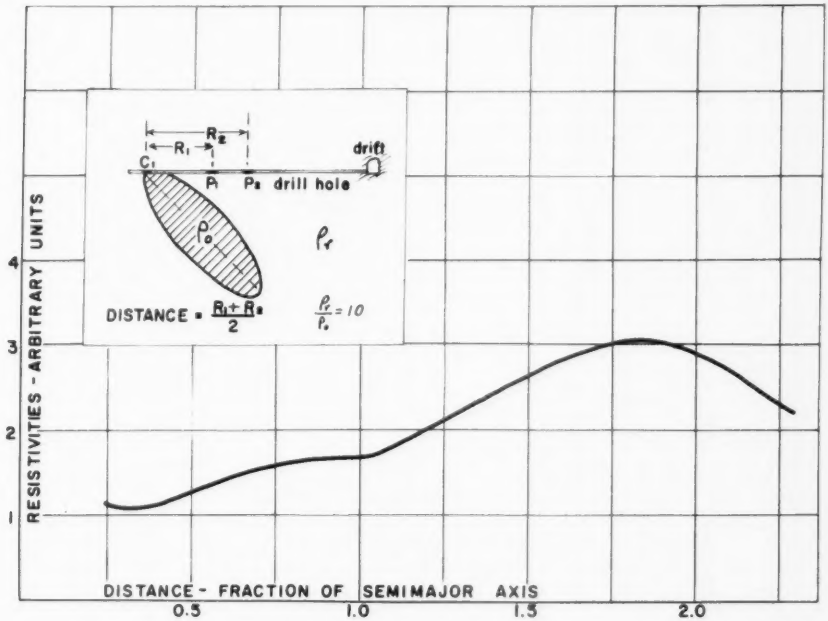

FIG. 4. Theoretical resistivity profile from a dipping prolate spheroidal conductor with current electrode at the end of the spheroid.

the current electrode equal to the largest distance the body extends from the intersection.

The case of an ore body whose long axis makes an angle of 45° with a drill hole or drift and which is intersected close to its end is shown in Fig. 4. The sharp increase in calculated resistivity values commences at a distance from the electrode slightly greater than half the conductor length. The values rise to a maximum at a distance approximately equal to the conductor length and then decrease.

COMPARISON WITH FIELD RESULTS

During tests at a mine in Western Canada where the conducting ore body dipped approximately 45°, one current electrode was placed on the upper end

of the remaining ore, about 250 feet below the surface. The other current electrode was on the earth's surface a long distance from the ore in a direction along the dip of the body. The potentials were measured in a horizontal drift nearly over the dipping axis of the conductor. The resistivity profile obtained from the measurements is shown in Fig. 5.

There is a very marked similarity between the experimental and the theoretical curve. Both show low values close to the electrode, then a slow increase for

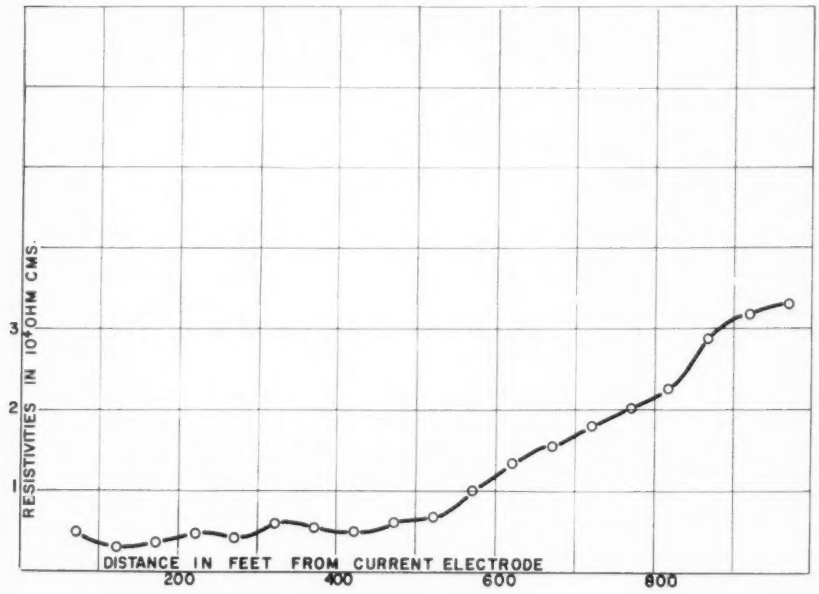

FIG. 5. Resistivity profile from a dipping ore body with current electrode in the upper end of the body.

considerable distance, followed by a very marked change in slope of the curve. Practical considerations prevented the experimental curve being further extended but it appears to be approaching a maximum at slightly more than 1,000 feet. The magnitude of the long dimension of the ore is not as yet known but it seems likely that it extends to at least 1,000 feet along its dip.

CONCLUSIONS

It appears that for spindle-like ore bodies, one dimension of which is much greater than the other two, there is a relation between the length of the body and the distance from the current electrode at which the calculated resistivity profile abruptly changes slope. For nearly vertical bodies this point marks the length.

As the dip of the body decreases the change in slope occurs at a distance which is a smaller fraction of the body length. The method provides a rapid means of determining whether the longer axis of the conductor is short and thus warrants no further investigation, or is extensive enough to justify investigation by drilling. In conjunction with available geological data it should provide a reasonably accurate estimate of conductor length.

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DISCUSSION OF PAPER BY A. R. CLARK ENTITLED "THE DETERMINATION OF THE LONG DIMENSION OF CONDUCTING ORE BODIES"

DR. BRUNO KUNZ*

When J. N. Hummel published his first apparent resistivity curves some 30 years ago, he used coordinates with a linear scale. A short time later it was found that such master curves are universally usable only when plotted on logarithmic scales. The resaon for this is that the shape of the curves does not depend upon the *absolute* electrode spacing and the *absolute* resistivity values but only on the *relative* values. This, naturally, also holds true for the examples shown by A. R. Clark. The curves as shown by him reveal a resistivity ratio of $\rho_r/\rho_0 = 10$. In the same way, the "Distance as a fraction of the Semimajor Axis" is a quotient. Both coordinates should therefore be presented in a logarithmic scale. When so plotted, the characteristic properties of the curves are much more conspciuous and are very different from those when linear scales are used. The remarks made by the author relative to the shape of the curves may have to be revised.

As an example for the change of the characteristic of the curves, the curve in figure 2† of the present paper has been plotted on double logarithmic paper. I believe the more compact character of the curve would be more recognizable.

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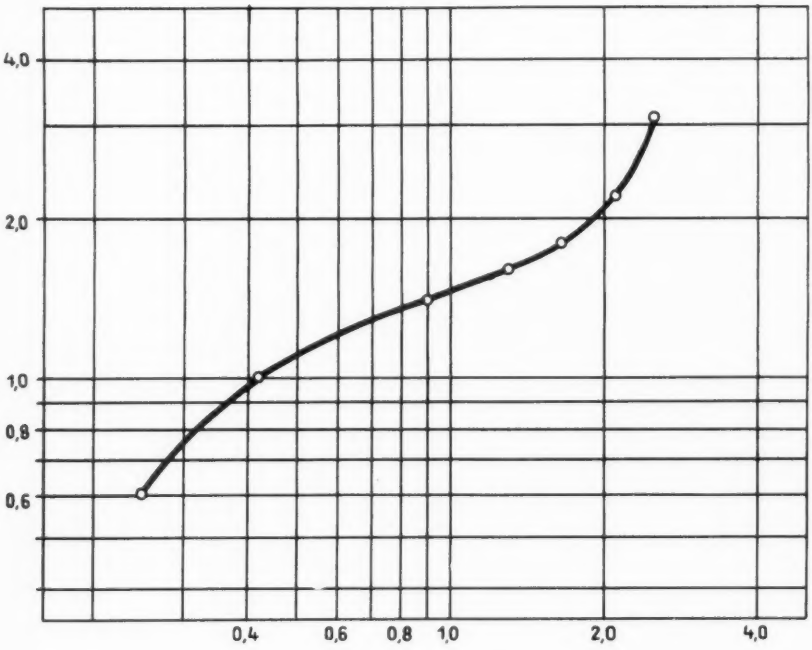
† See illustration on next page.



REPLY TO THE DISCUSSION BY DR. KUNZ

A. R. CLARK

It is quite true that in order to prevent the shape of curves depending on the absolute values of the resistivities and the electrode spacings, the quantities to be plotted must be expressed as ratios. Once this has been done the scale of plotting is chosen to illustrate best a particular characteristic of these ratios.

In the case of the curves shown the horizontal direction represents the distance in terms of the length of the semimajor axis, while the vertical direction represents values which are proportional to the resistivity of the rock surrounding the conductor, and not as is implied by Dr. Kunz's comments on the ratio ρ_r/ρ_0.

The curves are intended to illustrate the relation between the magnitude of the long dimension of an ore body and the point on the resistivity curve at which values begin to increase sharply. This can be done as well using a linear scale as a logarithmic one.

GEOPHYSICS, VOL. XXI, NO. 2 (APRIL, 1956), PP. 479–484, 2 FIGS.

MUTUAL ELECTROMAGNETIC COUPLING OF LOOPS OVER A HOMOGENEOUS GROUND—AN ADDITIONAL NOTE*

JAMES R. WAIT†

ABSTRACT

Further computations are presented for the mutual impedance between small wire loops over a semi-infinite conductor. The cases considered are where the axes of the loops are parallel to the interface.

In a previous paper (Wait, 1955), a number of formulae were listed pertaining to the electromagnetic coupling between small wire loops over a homogeneous conductive flat ground. The mutual impedance for various orientations of the loops were presented in graphical form. It is the purpose of this sequel to extend the earlier results. The cases considered are when the axes of both loops are parallel to, and above the ground.

Choosing a rectangular coordinate system (x, y, z), the source loop can be represented by a y-directed magnetic dipole of strength c, at (o, o, h) with respect to the conductive half-space defined for all negative values of z. The formal solution of this problem has been given previously (Wait, 1953). The magnetic potential Φ, for $z>o$ is given by

$$\Phi = -c\frac{\partial}{\partial y}\left\{\frac{1}{[x^2+y^2+(z-h)^2]^{1/2}} + \int_0^\infty \frac{(\lambda^2+i\sigma\mu_0\omega)^{1/2}-\lambda}{(\lambda^2+i\sigma\mu_0\omega)^{1/2}+\lambda} \cdot e^{-\lambda(z+h)} \cdot J_0[\lambda(x^2+y^2)^{1/2}]d\lambda\right\} \tag{1}$$

where σ is the conductivity of the ground, $\mu_0 = 4\pi\times 10^{-7}$ and ω is the angular frequency. Equation (1) is valid subject to significant distances in the air being small compared to the free-space wavelength. The magnetic fields are obtained from

$$\vec{H}^p + \vec{H}^s = -\operatorname{grad}\Phi \tag{2}$$

where the primary fields are affixed with a superscript p and the secondary fields resulting from the presence of the conducting half-space are affixed with a superscript s. The primary components are then given by

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$$H_x^p = 3xyc/r^5$$
$$H_y^p = 3y^2c/r^5 - c/r^3 \tag{3}$$
$$H_z^p = 3y(z - h)c/r^5$$

where

$$r = [x^2 + y^2 + (z - h)^2]^{1/2}.$$

The secondary components are written conveniently, after a change of variable, as follows

$$H_x^s = c(xy/\rho^2)\delta^{-3}[(2/B)T_2(A, B) - T_0(A, B)]$$
$$H_y^s = c(y^2/\rho^2)\delta^{-3}[(1 - x^2/y^2)(1/B)T_2(A, B) - T_0(A, B)] \tag{4}$$
$$H_z^s = c(y/\rho)\delta^{-3}T_1(A, B)$$

where

$$T_0(A, B) = \int_0^\infty F(g)gJ_0(gB)dg$$
$$T_1(A, B) = \int_0^\infty F(g)gJ_1(gB)dg \tag{5}$$
$$T_2(A, B) = \int_0^\infty F(g)J_1(gB)dg$$

with

$$F(g) = \frac{(g^2 + 2i)^{1/2} - g}{(g^2 + 2i)^{1/2} + g} e^{-gA}g \tag{6}$$

and

$$A = (z + h)/\delta, \qquad B = \rho/\delta, \qquad \delta = (2/\sigma\mu_0\omega)^{1/2}, \qquad \rho = (x^2 + y^2)^{1/2}.$$

The integrals are not easily evaluated. The first two, T_0 and T_1 however, were programmed for an electronic computer and numerical values were given

TABLE I

REAL PART OF $T_2(A, B)$

$A \backslash B$	0.1	0.2	0.5	1.0	1.5	2.0	3.0
0.5	.0097	.0190	.0439	.0767	.0887	.0879	.0705
1.0	.0053	.0104	.0248	.0460	.0570	.0601	.0542
1.5	.0032	.0063	.0152	.0290	.0378	.0423	.0417
2.0	.0019	.0041	.0096	.0192	.0259	.0304	.0319
3.0	.0007	.0017	.0039	.0093	.0129	.0167	.0189
5.0	.0001	.0002	.0022	.0022	.0031	.0057	.0068

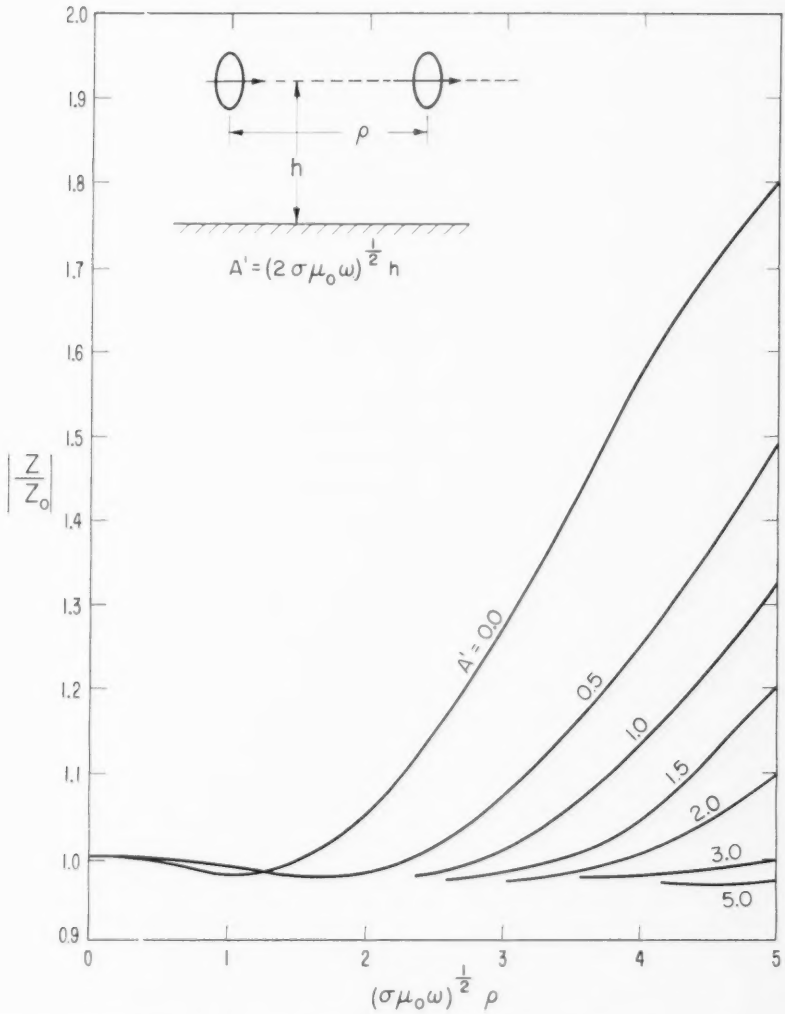

FIG. 1a. The mutual impedance ratio for co-axial loops with axes parallel to ground showing dependence on conductivity, frequency separation and height.

TABLE II

IMAGINARY PART OF $T_2(A, B)$

$A \backslash B$	0.1	0.2	0.5	1.0	1.5	2.0	3.0
0.5	.0302	.0595	.1051	.1234	.1035	.0769	.0370
1.0	.0090	.0192	.0440	.0617	.0617	.0525	.0304
1.5	.0037	.0087	.0214	.0332	.0372	.0353	.0237
2.0	.0017	.0043	.0121	.0189	.0229	.0240	.0183
3.0	.0002	.0012	.0050	.0068	.0098	.0116	.0104
5.0	.0000	.0000	.0002	.0009	.0022	.0029	.0033

by Wait (1955) for A from 0.5 to 5.0 and B from 0.1 to 3.0. The integral T_2 can be obtained most readily by noting that

$$T_2(A, B) = \int_A^\infty T_1(A, B)dA \tag{7}$$

and carrying out the integration numerically. Using this process the real and imaginary parts of $T_2(A, B)$ are listed in Tables I and II respectively.

Using the above results, the mutual impedance Z between loops with axes parallel to the ground can be obtained. Two important cases not discussed in the previous paper are illustrated in Figs. 1 and 2 and are denoted as IX and X so to render continuity with the eight examples that were discussed there. They are itemized as follows:

IX Co-axial loops, with axes horizontal, both at height h above the ground.

$$Z/Z_0 = 1 + (B^2/2)[T_2(A', B) - BT_0(A', B)] \tag{8}$$

with $Z_0 = 2k$ and $A' = (2\sigma\mu_0\omega)^{1/2}h$

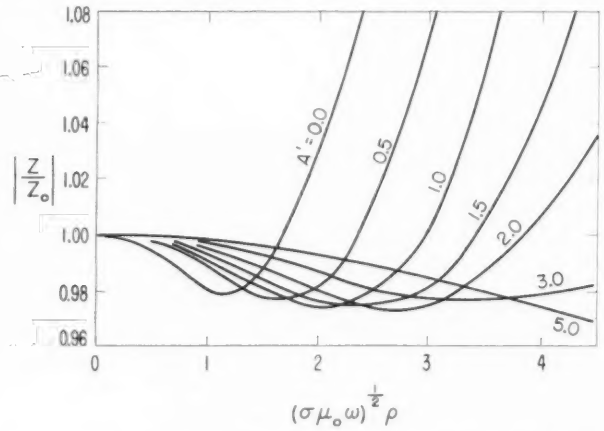

FIG. 1b. The mutual impedance ratio for co-axial loops with axes parallel to ground showing dependence on conductivity, frequency, separation and height.

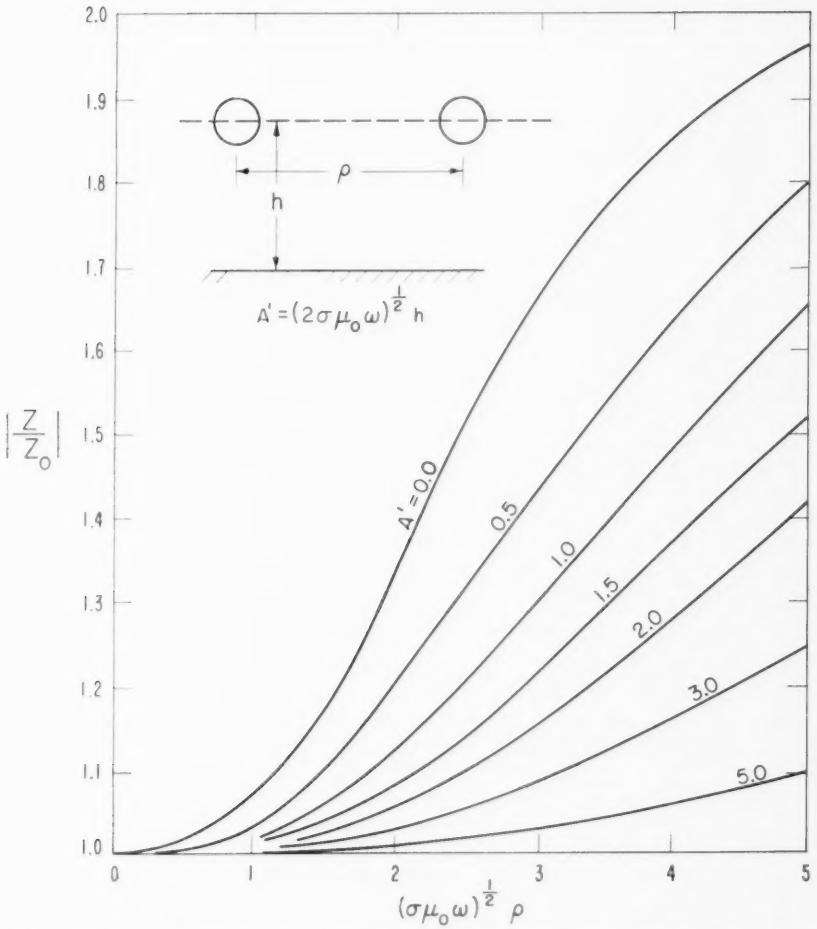

FIG. 2. The mutual impedance ratio for co-planar loops with axes parallel to ground showing dependence on conductivity, frequency separation and height.

X Co-planar loops, with axes horizontal, both at height h above the ground.

$$Z/Z_0 = 1 + B^2 T_2(A', B) \tag{9}$$

with $Z_0 = k$.

As before Z_0 is the mutual impedance between the two loops at separation ρ in the free space and k is a constant. The magnitude of the ratio Z/Z_0 for the two cases are plotted in Figures 1 and 2 employing the numerical data of T_0 and T_2

for A from 0.5 to 5.0. The limiting forms of IX and X when $A'=0$, corresponds to cases II and III in the previous paper and these are also reproduced in Figs. 1 and 2. It can be seen that there is a gradual transition in the value of Z as the loops rise from the surface of the ground.

A very significant feature of the curves for the co-axial loops, shown in Fig. 1, is the initial decrease of the ratio $|Z/Z_0|$ from unity as the loop separation increases from zero. For larger values of the separation, the ratio Z/Z_0 finally swings up to values greater than unity. It would therefore appear from the standpoint of minimizing the response of the over burden in an airborne electromagnetic prospecting scheme, that the co-axial loop arrangement is to be preferred. This remark of course would also apply when the loops were on the surface of the ground.

REFERENCES

Wait, J. R., 1955, Mutual electromagnetic coupling of loops over a homogeneous ground: Geophysics, v. 20, p. 630–637.

Wait, J. R., 1953, Induction by a horizontal oscillating magnetic dipole over a conducting homogeneous earth: Trans. Amer. Geophys. Union, v. 34, p. 185–189.

DEPARTMENTS

PATENTS

O. F. RITZMANN†

GRAVIMETRIC PROSPECTING

U. S. No. 2,721,481. K. D. Rainsberg. Iss. 10/25/55. App. 3/31/53.

Gravitymeter. A gravimeter for use as an altimeter having an eccentrically-pivoted mass with an armature suspended between the poles of a permanent magnet whose attraction supports the mass.

U. S. No. 2,726,074. R. W. Ketchledge. Iss. 12/6/55. App. 11/14/47, 5/19/50 and 9/1/53. Assign. Bell Telephone Laboratories, Inc.

Acceleration Measuring System. A device for measuring steady acceleration having a piezoelectric or magnetostrictive transducer in a case which is mounted eccentrically on a motor-driven shaft perpendicular to the acceleration to be measured and which also produces a phase-reference voltage, the a-c output from the transducer being fed to a phase-sensitive rectifier whose output is indicated.

MAGNETIC PROSPECTING

U. S. No. 2,721,974. O. H. Schmitt. Iss. 10/25/55. App. 8/7/44. Assign. U.S.A.

Magnetometer. A magnetic detector of the fluxgate type whose exciting frequency is doubled and used as reference signal of a discriminator to which the detector output is applied, the discriminator producing sum and difference voltages whose difference is indicated.

U. S. No. 2,725,504. W. C. Dunlap, Jr. Iss. 11/29/55. App. 11/29/51. Assign. General Electric Co.

Hall Effect Device. A Hall effect device having a single Hall plate whose surfaces are insulated and sandwiched between two ferro-magnetic plates and with electric terminals on the four edges of the plate.

U. S. No. 2,725,551. W. C. Anderson. Iss. 11/29/55. App. 6/28/44. Assign. U.S.A.

Magnetometer System. A magnetic detector of the fluxgate type using four saturated core elements connected in two bridge circuits so that the flux build-up in the elements of one circuit is opposite in polarity to the flux build-up in the other circuit, and the outputs added so as to cancel the effect of fluctuations in exciting voltage.

U. S. No. 2,727,206. C. M. Ryerson. Iss. 12/13/55. App. 1/14/47.

Apparatus for Detecting a Magnetic Field. A magnetic detector having a flux valve whose output is connected to a differential peak amplifier and rectifier supplying current to a feedback coil to neutralize the field component detected, the current in the coil being measured.

U. S. No. 2,727,207. J. J. Jones. Iss. 12/13/55. App. 9/19/52.

Device for Measuring Magnetic Field Intensity and Pole Direction. A magnetic detector having a mercury-filled insulating tube with a pair of electrodes connected to an amplifier and indicator and an electromagnetically-driven diaphragm which oscillates the mercury in the tube.

RADIOACTIVITY PROSPECTING

U. S. No 2,721,943. F. C. Armistead. Iss. 10/25/55. App. 10/21/50. Assign. Texaco Development Corp.

Radiation Detections. A gamma-ray detector using a translucent liquid luminophor and a gas-filled photo-electric detector to produce gas amplification of the scintillations.

† Gulf Oil Corporation, Patent Department.

U. S. No. 2,721,945. W. E. Sell and J. A. Forrester. Iss. 10/25/55. App. 11/13/48 and 8/9/51. Assign. Research, Inc.

Geophysical Exploration. A method of radioactivity prospecting in which the natural radioactivity over a considerable area is measured just above the surface of the ground without disturbing the soil and the regions of maximum radiation used to delineate the oil deposit.

U. S. No. 2,722,610. G. Herzog. Iss. 11/1/55. App. 3/9/48 and 6/23/51. Assign. The Texas Co.

Prospecting. A radioactivity prospecting method in which the natural gamma rays are caused to impinge on a foil to produce beta rays whose energy distribution is measured.

U. S. No. 2,724,060. S. A. Scherbatskoy. Iss. 11/15/55. App. 9/5/51.

Radiation Detector. A gamma-ray detector whose cathode plates are formed by an undulating ribbon and having a central anode wire connected to high potential and an indicator and also having auxiliary anode wires maintained at an intermediate potential.

U. S. No. 2,725,484. T. M. McKee. Iss. 11/29/55. App. 12/5/51. Assign. Texaco Development Corp.

Apparatus for Detecting Penetrative Radiation. A scintillation counter having a series of light-transparent sheets each having a mono-molecular layer of a normally-opaque inorganic material of high density.

U. S. No. 2,727,154. W. W. Goldsworthy. Iss. 12/13/55. App. 2/26/52. Assign. U.S.A.

Radiation Detector. A scintillation counter having a crystal responsive to alpha particles followed by a crystal responsive to beta and gamma rays which is in contact with a photomultiplier tube.

SEISMIC PROSPECTING

U. S. No 2,720,834. R. L. Davis. Iss. 10/18/55. App. 12/21/49. Assign. Sun Oil Co.

Shotline Trap. A spear which may be inserted into a loaded shot hole and having two parallel shafts arranged so that rotation of one shaft rotates a jack screw which forces the barbs of the spear into the sides of the hole.

U. S. No 2,720,933. W. T. Born, L. Y. Faust and A. Wolf. Iss. 10/18/55. App. 12/4/52. Assign. Geophysical Research Corp.

Seismic Geophysical Exploration. A method of seismic shooting using shots spaced transversely to the profile over a distance equal to at least one wave length and fired in time sequence so that reinforcement occurs for reflections from a horizon of a particular attitude, and repeating with different time sequences so as to determine the sequence which gives maximum reflection energy.

U. S. No. 2,721,617. R. G. Piety. Iss. 10/25/55. App. 6/12/50. Assign. Phillips Petroleum Co.

Method of Seismic Prospecting. A seismic shooting method in which a group of shot holes are drilled close together and each sprung to enlarge it both radially and vertically, and a vertical string of charges in all holes fired simultaneously to simulate a strong point source.

U. S. No. 2,723,387. M. Slavin III. Iss. 11/8/55. App. 5/18/53. Assign. United Geophysical Corp.

Seismic Prospecting System. A seismograph avc system in which the gain control effected by the avc loops is controlled by the signal from an external oscillator whose frequency is outside the range of seismic frequencies.

U. S. No. 2,724,452. W. A. Sorge. Iss. 11/22/55. App 3/30/51. Assign. Esso Research and Engineering Co.

Seismic Prospecting. An air-shooting system using Primacord in the form of an inverted V whose legs make acute angles with the ground toward and away from the detectors, the respective angles being related to the propagation velocities involved.

U. S. No. 2,724,453. B. D. Lee. Iss. 11/22/55. App. 5/4/51. Assign. The Texas Co.

Methods of Identifying Seismic Waves. A system of shooting to differentiate between reflected and diffracted waves by establishing the strike of the diffracting fault and reshooting with a new set up which would at least double the step out of a reflection and comparing the second observed travel times with those first observed.

U. S. No. 2,724,819. G. Peterson. Iss. 11/22/55. App. 7/1/48, 12/28/51 and 6/10/52. Assign. Phillips Petroleum Co.

Electrostatic Seismometer. A capacitative seismometer whose plates have juxtaposed projections between which is suspended a series of blocks of material having a high dielectric constant.

U. S. No. 2,725,492. W. H. Allan. Iss. 11/29/55. App. 4/1/53.

Dual Range String Accelerometer. An accelerometer having unequal masses fastened to the ends of a taut wire with the inner side of the mass against stops so that axial acceleration tensions the wire which is in a magnetic field so that incidental vibration sets up an induced current whose frequency is measured.

U. S. No. 2,725,527. C. D. McClure. Iss. 11/29/55. App. 1/23/50. Assign. Socony Mobil Oil Co., Inc.

System for Measuring Amplifier Phase Shift. A seismic amplifier testing device having a pair of magnets rotating on a common shaft near two sets of coils with the induced voltage from one set of coils connected to the horizontal sweep of a c-r tube and the voltage from the other set of coils connected through the amplifier to produce vertical deflection of the c-r beam.

U. S. No. 2,725,534. W. B. Hemphill. Iss. 11/29/55. App. 3/8/51. Assign. Socony Mobil Oil Co., Inc.

Recording Seismic Waves Without Phase Distortion. A seismograph channel in which the non-linear phase-frequency characteristic is corrected by delaying each frequency by an amount equal to the departure from linearity and phase shifting all frequencies by the zero intercept angle of the resulting straight line.

U. S. No. 2,725,548. W. T. Harris. Iss. 11/29/55. App. 7/24/51. Assign. The Harris Transducer Corp.

Variable-Capacitor Transducer. A pressure geophone having between two plates of a condenser a material whose dielectric-constant varies with pressure and is subjected to the ambient pressure or pressure generated by vibration of a geophone mass.

U. S. No. 2,725,821. H. W. Coleman. Iss. 12/6/55. App. 2/29/52. Assign. Hercules Powder Co.

Circuit Closing Means and Blasting Assembly. A device for introducing a short delay between two cap circuits having a bridge wire in series with the first circuit which ignites an explosive so as to fuse a material which is conducting in the liquid state to close the second circuit.

U. S. No. 2,725,822. I Janelid. Iss. 12/6/55. App. 3/29/52. Assign. Hercules Powder Co.

Switch and Method for Blasting. A device for introducing a delay between two firing circuits having n the first circuit an extra cap in a well in the device so that detonation of the cap releases a prop under a switch which closes the second circuit.

U. S. No. 2,725,823. J. J. Henschke, Jr. Iss. 12/6/55. App. 9/27/51. Assign. Olin Mathieson Chemical Corp.

Electric Blasting Caps. A protective cover for the bare terminals of cap wires made of insulating

plastic material which is crimped around the terminals to hold them in contact but prevents their contacting extraneous circuits.

U. S. No. 2,726,131. J. D. Skelton. Iss. 12/6/55. App. 12/18/52. Assign. Esso Research and Engineering Co.

Modulated Galvanometer Recording of Transient Signals. A system for channelizing galvanometer deflections by using the signal to amplitude-modulate a carrier to which the galvanometer is tuned and masking the trace to record only the zero transits of the light beam so that large galvanometer swings will produce faint lines and small swings produce darker lines.

U. S. No. 2,726,290. E. H. Meier. Iss. 12/6/55. App. 6/11/49. Assign. Esso Research and Engineering Co.

Surgeless Electronic Variable Resistor and Attenuator. A surgeless attenuator for an avc system having a signal-divider circuit whose controllable element is two tubes in parallel with their grid and cathode in the signal circuit and control voltage applied to both anodes.

U. S. No. 2,728,405. A. A. Brant. Iss. 12/27/55. App. 5/26/53. Assign. Newmont Mining Corp.

Seismic Method of Geophysical Exploration. A system of continuous wave seismic testing using an electromechanical source of varying frequency and a spaced detector and observing the frequency change from one condition of maximum received energy to the next higher frequency at which such reinforcement occurs.

WELL LOGGING

Re. 24,076 (Original No. 2,633,783). C. Laval, Jr. Iss. 10/18/55. App. 2/13/50, 4/7/53 and 3/1/54.

Apparatus Adapted to Provide Photographic Records of Wells and the Like. A photographic logging apparatus having a lamp and a camera, electric power being supplied from the surface to advance the film and charge a condenser which is switched to discharge through the lamp when the power is interrupted.

U. S. No. 2,719,361. R. F. Montgomery and N. L. H. Koot. Iss. 10/4/55. App. 11/5/52.

Calipering Method and Apparatus. A caliper logging device having arms located in slots of a telescoping bit stem which is released and extended when a recording device is lowered through the drill pipe and which records movement of the arms as the drill pipe is raised.

U. S. No. 2,719,362. R. F. Montgomery and N. L. H. Koot. Iss. 10/4/55. App. 12/9/52.

Method and Apparatus for Calipering. A caliper logging device having three caliper arms with cams and cam followers driving pistons connected to a single recording piston.

U. S. No. 2,719,363. R. F. Montgomery and N. L. H. Koot. Iss. 10/4/55. App. 1/10/53.

Calipering Method and Apparatus. A caliper logging device having a bit on a slotted telescoping stem which is latched to the drill pipe and is extended when the calipering device is lowered through the drill pipe so that a caliper log can be run when withdrawing the drill pipe.

U. S. No. 2,719,485. A. Z. Bendar. Iss. 10/4/55. App. 1/9/50. Assign. Eastman Oil Well Survey Co.

Magnetic Control Devices. A well surveying device which is tripped by movement of a permanent magnet which closes a switch and having a telescoping section carrying another permanent magnet which is brought into engagement with the first magnet when the instrument is set on bottom.

U. S. No. 2,719,948. C. W. Zimmerman. Iss. 10/4/55. App. 5/28/52. Assign. Schlumberger Well Surveying Corp.

Magnetically Investigating Material at the Wall of a Well Bore. A device for magnetically logging small areas of a borehole wall using an inductance shorter than the borehole diameter pressed against

the borehole wall by a spring and with the leads to the inductance passing through a pressure-resistant seal to avoid pressure on the conductors.

U. S. No. 2,720,584. G. S. Sloughter. Iss. 10/11/55. App. 11/22/49. Assign. Schlumberger Well Surveying Corp.

Frequency Discriminator. An f-m discriminator system for multichannel telemetering having a band-pass filter and a limiter which control a pulse generator and trigger circuit to produce square pulses whose difference in alternate pulse widths indicates the quantity being metered.

U. S. No. 2,721,110. B. G. Price. Iss. 10/18/55. App. 5/25/53. Assign. Tuboscope Co.

Tubing Calipers. A tubing caliper having a plurality of circumferentially-spaced feeler arms with followers which control movement of recording pens so that the pens record the maximum variation in diameter detected by the feelers.

U. S. No. 2,721,944. R. J. Ruble. Iss. 10/25/55. App. 9/9/50. Assign. Texaco Development Corp.

Method of and Apparatus for Exploring Radioactive Strata. A radioactivity logging detector having a gas-filled cathode envelope coated on the outside with a substance which reacts to high energy gamma rays to produce neutrons and coated on the inside with a material which reacts to neutrons to produce ionizing particles and having a central anode wire.

U. S. No. 2,722,282. P. McDonald. Iss. 11/1/55. App. 8/24/50. Assign. Socony Mobil Oil Co., Inc.

Acoustic Well Logging System. An acoustic logging apparatus having a liquid-filled cylinder with a crystal transmitter and a liquid-filled cylinder with a crystal detector whose output pulses are recorded at the surface, and a material of low acoustic conductivity (lead) interposed between the cylinders so as to attenuate the direct wave to an amplitude comparable to that of the wave through the formations.

U. S. No. 2,722,657. H. Janssen. Iss. 11/1/55. App. 7/3/53. Assign. Perforating Guns Atlas Corp.

Means for Detecting Changes in Dielectric Constant of Thin Strata of Lithological Formations Traversed by a Borehole. A dielectric-constant logging device having a cylindrical conducting case forming one plate of a condenser whose other plate is a short cylinder axially spaced from the case by an insulator of large diameter and low dielectric constant.

U. S. No. 2,723,374. P. S. Williams. Iss. 11/8/55. App. 4/9/53. Assign. Esso Research and Engineering Co.

Electromagnetic Prospecting from Bore Holes. An electromagnetic logging system in which current is passed between surface electrodes located some distance on each side of the borehole and the field is picked up by quadrature coils whose axes are horizontal and have a gyro-maintained orientation, the phase and amplitude of the emfs picked up being indicated at the surface.

U. S. No. 2,723,375. N. A. Schuster. Iss. 11/8/55. App. 3/2/53. Assign. Schlumberger Well Surveying Corp.

Induction Logging Apparatus. An induction logging system using a transmitter coil and a receiver coil connected in an oscillating circuit whose frequency changes with phase shift of currents in the coils due to conductivity of the surrounding formations, the frequency being recorded at the surface of the ground.

U. S. No. 2,724,068. A. D. Garrison. Iss. 11/15/55. App. 9/26/52. Assign. Texaco Development Corp.

Measurement of Radiation. A gamma-ray counter of the gas-amplification type employing ammonia and having an ammonia-absorbing material such as silica gel inside the envelope to provide temperature compensation by the material giving up ammonia at high temperatures as encountered in deep wells.

U. S. No. 2,724,267. D. C. Bond and N. B. Russell. Iss. 11/22/55. App. 8/26/48. Assign. The Pure Oil Co.

Method for Measuring Flow of Fluid in Earth Bores. A system for measuring flow in a fluid injection well by injecting an electrically-identifiable material into the fluid a short distance above a detector of the material, lowering the assembly into the well and obtaining a signal proportional to the concentration of the injected material.

U. S. No. 2,724,779. A. S. McKay. Iss. 11/22/55. App. 12/12/50. Assign. The Texas Co.

Counters for Discriminating Between Gamma Rays of Different Energies. A counter for high-energy gamma rays using a high atomic number cathode coated with a low atomic number metal so that weak electrons will be absorbed but energetic electrons will penetrate the coating and produce an ion pulse in the gas.

U. S. No. 2,725,282. S. E. Buckley and W. D. Mounce. Iss. 11/29/55. App. 4/30/52. Assign. Esso Research and Engineering Co.

Well Logging Apparatus. A well-logging apparatus having tubular arms which penetrate the mud sheath and inject a liquid oxidizing agent from a pressure tank into the formation and subsequently measures the formation temperature with a thermocouple on the same or adjacent arms.

U. S. No. 2,725,283. W. D. Mounce, J. H. Dunaway and M. C. Terry. Iss. 11/29/55. App. 4/30/52. Assign. Esso Research and Engineering Co.

Apparatus for Logging Well Bores. A device for testing for oil in the borehole wall by forcing the end of a small cylinder through the mud film against the formation and introducing an oxidizing agent into the cylinder whose temperature rise is recorded.

U. S. No. 2,725,485. S. A. Scherbatskoy. Iss. 11/29/55. App. 8/3/51. Assign. Perforating Guns Atlas Corp.

Radioactivity Well Logging. A radioactivity logging apparatus having a neutron source and a plurality of gamma-ray counters sensitive to different energies connected to coincidence circuits and an anti-coincidence circuit.

U. S. No. 2,725,486. J. E. Walstrom. Iss. 11/29/55. App. 12/9/52. Assign. California Research Corp.

Method and Apparatus for Well Logging. A caliper logging device in which the caliper arms move radioactive sources toward or away from a radioactivity detector whose output is indicated.

U. S. No. 2,725,523. H.-G. Doll. Iss. 11/29/55. App. 6/6/52. Assign. Schlumberger Well Surveying Corp.

Multiple Coil Apparatus for Induction Well Logging. An electromagnetic logging sonde having two closely-coupled coils on a cylindrical form with one coil excited by a-c and the other coil connected to apparatus which resolves the induced voltage into signals indicative of magnetic susceptibility and electrical conductivity.

U. S. No. 2,725,713. A. Blanchard. Iss. 12/6/55. App. 4/6/48, 5/13/52 and 7/22/52. Assign. Schlumberger Well Surveying Corp.

Cable Construction. An electric logging cable with gradually-tapering strands in the load-carrying sheath and which have a coating of tapering thickness to equalize the diameter of the strands over the entire length.

U. S. No. 2,726,338. C. Goodman. Iss. 12/6/55. App. 10/18/51. Assign. Schlumberger Well Surveying Corp.

Method of Locating Material. A radioactivity logging method of locating particular nuclei by ir-

radiating the borehole wall with gamma rays of sufficient energy to exceed the photodisintegration threshhold of the particular nuclei but insufficient to effect photodisintegration of surrounding elements.

U. S. No. 2,726,365. K. A. Bilderback. Iss. 12/6/55. App. 6/12/52. Assign. Schlumberger Well Surveying Corp.

Electromechanical Computers. A computer for an electric logging apparatus having an error-controlled servo which picks off part of one voltage to be balanced against a second voltage, and the servo also adjusting an impedance which is in the indicating circuit.

U. S. No. 2,726,848. R. F. Montgomery, N. L. Koot, and M. A. Garrison. Iss. 12/13/55. App. 9/27/54. Assign. Montgomery and Koot.

Logging Sub. A sub which may be connected in the drill string and which has telescoping sections normally latched together by fingers held outwardly by an internal sleeve, the fingers being released by movement of the sleeve effected by the logging tool lowered through the drill string.

U. S. No. 2,727,087. C. O. Hull. Iss. 12/13/55. App. 4/18/52. Assign. General Electric Co.

Armored Oil Well Cable. A well cable whose conductors are covered with plastic insulation and an open-mesh glass braid and a spiral armor so that the plastic will extrude through the glass mesh on curing and adhere to the armor.

U. S. No. 2,727,155. G. Herzog and A. S. McKay. Iss. 12/13/55. App. 3/3/51. Assign. The Texas Co.

Scattered Gamma Ray Well Logging. A gamma-ray well logging sonde having a source of gamma rays on its axis, a gamma-ray detector spaced from the source by two to three times the borehole diameter and a horizontal gamma-ray shield spaced one inch from the source.

U. S. No. 2,728,047. H.-G. Doll. Iss. 12/20/55. App. 6/13/52. Assign. Schlumberger Well Surveying Corp.

Methods and Apparatus for Logging Spontaneous Potentials in Wells. An s-p logging system in which a-c is fed to a pair of electrodes one of which is near the s-p electrode and the other some distance away so that signals proportional to the s-p, resistivity, and space rate of change of s-p are obtained which are used as input to a computing circuit which indicates the static s-p.

U. S. No. 2,728,225. H. E. Skibitzke. Iss. 12/27/55. App. 3/12/53.

Thermal Flowmeter. A well flowmeter having a probe with an electric heating coil and a thermistor to indicate the temperature rise, or a thermistor ahead of and another thermistor behind the heating element in the fluid path so that the direction of flow can be identified.

MISCELLANEOUS

U. S. No. 2,721,994. R. H. Brown. Iss. 10/25/55. App. 11/14/52. Assign. Westinghouse Air Brake Co.

Self-Balancing Electro-Magnetic Proximity Detector. An electromagnetic detector having an oscillating circuit with a coil whose change of inductance is detected by a discriminator connected to a motor which controls a variable condenser to restore the frequency to normal.

U. S. No. 2,722,605. R. L. Mills and F. J. McDonal. Iss. 11/1/55. App. 1/7/53. Assign. Socony Mobil Oil Co., Inc.

Balanced Phase Discriminator. A four-arm discriminator bridge whose adjacent arms have voltage applied by the coils of a center-tapped transformer and to which the second voltage is applied by separate transformers in each arm.

U. S. No. 2,722,609. G. W. Morgan, O. M. Bizzell, G. G. Manov and J. W. Hitch. Iss. 11/1/55. App. 7/11/52. Assign. U.S.A.

Radiation Analysis. A device for measuring the density of silt and having a bifurcated housing with one leg containing a source of beta rays covered by a foil window to produce bremsstrahlung radiation which passes through the silt and is detected by a scintillation counter in the other leg.

U. S. No. 2,723,228. P. J. Moore and A. Abdalla, Jr. Iss. 11/8/55. App. 11/3/54. Assign. National Lead Co.

Distillation Apparatus for the Determination of Oil and Water in Drilling Muds. A distillation apparatus having an electrically heated retort with an upper refluxing chamber and a delivery tube which passes through a large block of metal to form a condenser.

U. S. No. 2,724,114. S. Kaufman. Iss. 11/15/55. App. 10/16/50. Assign. Shell Development Co.

Phase-Comparison Radiolocation System. A radio location system using three spaced transmitters whose r-f differ by different audio frequencies, the first station transmitting a signal modulated by the interference frequency between stations two and three, and the third station transmitting a signal modulated by the interference between stations one and two, the mobile station receiving two pairs of frequencies whose beats are compared in phase.

U. S. No. 2,724,830. J. E. Hawkins. Iss. 11/22/55. App. 11/2/53. Assign. Seismograph Service Corp.

Radio Location System. A radio location system using four transmitters three of which are spaced and radiate position-indicating signals with the fourth transmitter radiating carrier signals which alternately operate the first and second transmitters, the carrier from the fourth transmitter being modulated by the signal from the third transmitter and alternately the first or second transmitter when operating.

U. S. No. 2,724,963. K. C. ten Brink. Iss. 11/29/55. App. 6/2/51. Assign. The Texas Co.

Determination of Effective Nonwetting Phase Permeability. A method of measuring permeability of a core by injecting mercury until the desired saturation by the non-wetting phase is attained and then measuring the pressure gradient required to flow the mercury while the saturation pressure is maintained.

U. S. No. 2,725,109. E. F. Bouvier. Iss. 11/29/55. App. 8/11/54.

Engine and Transmission Drive Assembly for Marsh Buggy. A marsh buggy having buoyant wheels whose axles are carried on a sub-frame below the main frame so that the wheels are below deck level and with the wheels on the two sides driven by two separate engines.

U. S. No. 2,725,281. D. C. Bond. Iss. 11/29/55. App. 12/29/50. Assign. The Pure Oil Co.

Exploration for Oil by Soil Analysis. A device for interpreting the results of areal geochemical measurements having a map with lamps or electromagnets located at the observation points whose brightness or pole strength is proportional to the measured concentration, and a translucent screen through which the halo may be seen or a non-magnetic screen with iron filings to indicate the halo.

SELECTED LIST OF U. S. PATENTS ISSUED DURING THE SECOND QUARTER OF 1955

Patent No.	*Subject**	*Patent No.*	*Subject**	*Patent No.*	*Subject**
2,719,361[a]	44	2,721,109	324	2,722,587	428
2,719,362[a]	44	2,721,110[a]	44	2,722,604	68
2,719,363[a]	44	2,721,267	460	2,722,605[a]	68
2,719,428	428	2,721,270	236	2,722,609[a]	308
2,719,430	428	2,721,271	236	2,722,610[a]	308
2,719,431	288	2,721,274	308	2,722,657[a]	128
2,719,485[a]	520	2,721,315	12	2,722,678	200
2,719,502	216	2,721,478	148	2,722,835	200
2,719,670	68	2,721,479	188	2,722,837	288
2,719,671	68	2,721,480	460	2,722,839	16
2,719,823	308	2,721,481[a]	180	2,723,228[a]	252
2,719,884	224	2,721,617[a]	360	2,723,312	224
2,719,926	140, 308	2,721,696	68	2,723,315	224
2,719,947	324	2,721,699	308, 68	2,723,351	308
2,719,948[a]	220	2,721,700	308, 68	2,723,357	140
2,719,949–953	140, 228	2,721,743	224	2,723,374[a]	128
2,719,964	324, 68	2,721,782	324	2,723,375[a]	128
2,719,965	68	2,721,783	160	2,723,386	484
2,719,969	316	2,721,905	484, 224	2,723,387[a]	372
2,720,107	188	2,721,906	224	2,723,562	148
2,720,108	168	2,721,918	428	2,723,564	460
2,720,111	428	2,721,919	428	2,723,589	416
2,720,113	288	2,721,942	196	2,724,058	236
2,720,116	16	2,721,943[a]	308	2,724,060[a]	308
2,720,191	148	2,721,944[a]	304	2,724,068[a]	308
2,720,558	224	2,721,945[a]	308	2,724,114[a]	312
2,720,582	308	2,721,970	228	Re. 24,092	448
2,720,584[a]	516	2,721,973	228	2,724,267[a]	276
2,720,593	236	2,721,974[a]	232	2,724,268	148
2,720,594	196	2,721,987	108	2,724,269	148
2,720,620	160, 324	2,721,989	324, 68	2,724,270	148
2,720,626	68	2,721,990	224	2,724,271	148
2,720,645	316	2,721,994[a]	132	2,724,272	148, 200
2,720,647	316	2,721,998	316	2,724,273	148, 200
2,720,648	316	Re. 24,082	200	2,724,304	420
Re. 24,075	412	Re. 24,084	316	2,724,333	48
Re. 24,076[a]	280	2,722,122	148	2,724,452[a]	360
2,720,783	68	2,722,123	200, 412	2,724,453[a]	360
2,720,784	200	2,722,124	16	2,724,553	68, 468
2,720,785	200	2,722,125	16	2,724,564	16
2,720,787	288	2,722,126	16	2,724,631	324
2,720,834[a]	136	2,722,127	16	2,724,760	288
2,720,933[a]	360	2,722,282[a]	8	2,724,779[a]	308
2,721,031	416	2,722,470	108	2,724,783	12
2,721,055	80	2,722,586	188	2,724,816	108

* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

Patent No.	Subject*	Patent No.	Subject*	Patent No.	Subject*
2,724,817	108	2,725,822[a]	32	2,727,208	484
2,724,818	484	2,725,823[a]	136	2,727,209	468
2,724,819[a]	376	2,726,038	68	2,727,229	312
2,724,825	316	2,726,039	312, 68	2,727,231	312
2,724,826	316	2,726,048	224	2,727,387	428, 484
2,724,827	316	2,726,049	224	2,727,388	148
2,724,828	316	2,726,074[a]	4, 180	2,727,392	412
2,724,830[a]	312	2,726,075	4	2,727,393	16
2,724,831	312	2,726,076	148	2,727,682	68
2,724,962	168	2,726,130	324	2,727,801	324
2,724,963[a]	276, 88	2,726,131[a]	160, 324	2,727,802	324
2,724,964	140	2,726,286	224	2,727,968	188
2,724,965	428	2,726,287	224	2,728,035	200
2,724,967	148	2,726,288	224	2,728,047[a]	116
2,724,969	148	2,726,289	324	2,728,063	484
2,724,970	148	2,726,290[a]	372	2,728,076	312
2,725,109[a]	490	2,726,305	188	2,728,217	168
2,725,191	68	2,726,335	236	2,728,219	412
2,725,192	68	2,726,338[a]	304	2,728,220	492
2,725,193	68	2,726,365[a]	116	2,728,222	440
2,725,281[a]	396	2,726,383	316	2,728,225[a]	148
2,725,282[a]	524, 172, 392	2,726,384	316	2,728,226	200
2,725,283[a]	524, 172, 392	2,726,385	316	2,728,227	200
2,725,430	224	2,726,386	316	2,728,228	188
2,725,484[a]	308	2,726,387	316	2,728,231	288
2,725,485[a]	304	2,726,457	216, 16	2,728,233	16
2,725,486[a]	44, 308	2,726,544	16	2,728,397	36
2,725,491	12, 140	2,726,546	148	2,728,405[a]	360, 76
2,725,492[a]	4	2,726,547	288	2,728,524	68
2,725,504[a]	232	2,726,550	16	2,728,577	224
2,725,523[a]	128	2,726,602	136	2,728,831	188
2,725,527[a]	344	2,726,848[a]	44	2,728,832	460
2,725,534[a]	348, 360	2,726,918	324	2,728,833	460
2,725,547	484	2,726,919	324	2,728,836	460
2,725,548[a]	376	2,727,087[a]	40	2,728,852	316
2,725,551[a]	232	2,727,096	224	2,728,862	308
2,725,556	316	2,727,097	224	2,728,863	308
2,725,557	316	2,727,098	224	2,728,868	4
2,725,713[a]	116	2,727,099	484	2,728,893	148
2,725,741	288	2,727,154[a]	308	2,728,901	108, 484
2,725,744	496	2,727,155[a]	304	2,728,902	108
2,725,746	16	2,727,206[a]	232	2,728,909	312
2,725,750	16	2,727,207[a]	232	2,728,910	316
2,725,821[a]	136, 388, 32				

REVIEWS

REVIEWS COMMITTEE

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Geomagnetic number of *Indian Journal of Meterology & Geophysics*, Vol. 5, Special Number, Dec. 1954, iv+240 pp.

This special issue, with an appropriate golden front cover, was issued in commemoration of the golden jubilee of the Magnetic Observatory at Alibag (Bombay). As is natural, the issue contains articles on the history of the Alibag observatory and of its predecessor, the Colaba observatory (1846–1906) in Bombay; biographies of the directors; a bibliography of papers issued from the observatory; and a description of the golden jubilee celebration on December 12, 1954. In addition there are twenty-five contributed papers from workers in geomagnetism from all over the world. Since none of these deal with geophysical prospecting, the titles will not be listed here. Specialists in geomagnetism will naturally wish to examine the entire issue.

Thomas A. Elkins
Gulf Research & Development Co.
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"Geophysical Prospection of Underground Water in the Desert by Means of Electromagnetic Interference Fringes," M. A. H. El-Said, Cairo University, Egypt, *Proceedings of the I.R.E.*, Vol. 44, No. 3, Jan. 1956.

This paper discusses a method for locating the depth to the water table employing electromagnetic waves of radio frequency and gives the results of some preliminary field work done in the Sahara desert where the low conductivity of the surface materials produces a favorable condition for the propagation of electromagnetic waves through the earth.

The method discussed is analogous to a method formerly employed in measuring the height of the ionosphere. A radio transmitter is connected to a dipole antenna laid on the earth's surface and the resulting field strength measured a short distance away. If the water table acts as a good reflector, the earth above it being a poor conductor, then the observed field strength will be that produced by the real antenna plus that produced by the image of the antenna in the water table reflector. If the

frequency of the radio transmitter be varied slowly through a suitable range, the observed field strength will show a series of maxima and minima because of the varying phase difference between signal from the real antenna and the signal from its image. Alternatively, the transmitter frequency may be kept constant while the distance to the receiver is varied. The signal will then diminish with distance but again should show a series of maxima and minima as the distance is varied. Using the first method, the depth to the reflecting layer may be computed from the observed frequency difference between successive maxima and the fixed receiver distance, provided the value of the earth dielectric constant and the velocity of the direct electromagnetic wave be known. Using the second method, a similar computation may be made using the observed distance between successive maxima.

The author discusses the factors which determine the applicability of the method and the choice of radio frequencies to be employed. He gives also the results of preliminary field work at two sites in the Sahara desert. Radio frequencies in the range 400 to 650 kc, were employed with the variable frequency method, and frequencies of 840, 940, and 1,040 kc using the variable distance method. The dielectric constant of the earth was determined in the field, by some method not described, and found to be 5.1 at one site and 7.5 at the other. These values are very low for natural earth materials *in situ*. If correct they certainly indicate complete absence of moisture. The velocity of the direct wave was estimated to be 0.75 that of the velocity of light. At the first site, identified as at Baharya Road (some 20 kilometers from the Pyramids), the depth to the water table was estimated to be about 600 meters, but no well had been drilled in the vicinity for a check. At the second site, at Abu Aweigla, Senai, the results were interpreted to indicate a water table at a depth of about 800 meters. A well drilled by the Standard Oil Company, some 20 kilometers away, encountered the first water at a depth of 790 meters.

The field data presented in the paper show very feeble maxima and minima and do not prove the applicability of the method to this reviewer's satisfaction. The author of the paper feels that the results are promising although he realizes the great difficulty involved in making sufficiently accurate determinations of field strength so that anomalies in the observed data may be properly interpreted. It is to be hoped that further work will be done properly to evaluate the method.

W. T. Born

Structural Geology for Petroleum Geologists. William L. Russell, McGraw-Hill Book Company, Inc., New York, 1955, 427 pp: $7.50.

In spite of varying opinions, rather forcefully expressed in past years, geophysicists and geologists seem now agreed that some knowledge of structural geology as well as of geophysical techniques should be in the working kit of any interpreter of seismic data. Experienced geophysicists who entered geophysical profession without academic training in geology, have acquired the necessary background by self-study and a process of osmosis resulting from professional contacts with other geophysicists and geologists. This new book by William L. Russell, Professor of Geology at Texas A. and M. College, is highly recommended to those geophysicists still engaged in this process, as well as to geologists entering the field of petroleum geology, who may feel the need of reviewing the subject.

Although written as a text book for geology students, the subject matter is treated in such fashion that it can be easily understood by readers with little or no prior geological knowledge. All geologic terms used are clearly defined. The author's style is clear and concise.

The scope of the book is rather strictly limited to the static or geometrical phase of the subject; that is to say, to discussions of structures in sedimentary beds and their relationship to the accumulation of petroleum, whether these structures be caused by tectonic movement or by stratigraphic causes. Only one short chapter entitled "Physical Principles and Model Studies," is devoted to a discussion of theoretical and experimental work related to the dynamics of deformation, and little mention is made of igneous and metamorphic rocks. After mastering the material in the book under review, the reader may wish to continue his education with the aid of books dealing more generally with structural geology, for example, "Outlines of Petroleum Geology" by E. S. Hills (reviewed by Dr. Nelson C. Steenland, in Geophysics, April, 1954).

This reviewer found that discussion of salt domes and the faulting associated therewith, and the

chapter on faults and their relationship to the accumulation of oil, to be particularly interesting and informative.

The author emphasizes the fact that the ability to visualize structural features in three dimensions and the ability to show structural concepts clearly by graphic methods are essential attributes of a successful structural geologist. To aid the student in attaining these abilities, the author has included a section called "Laboratory Problems." A student who completes all the exercises presented will have a good idea of how to handle the problems he will meet in practical work.

The volume is very well illustrated and adequate references are given in the text. An excellent bibliography is appended to each chapter. The publishers have adhered to their customary high standards in the make-up of the book.

W. T. Born

"Vorarbeiten für das Fadenpendel zur absoluten Schwerebestimmung" (Preliminary Developments of a Simple Pendulum for Absolute Gravity Determinations), Prof. Dr. A. Berroth, Wissenschaftliche Referate, I Teil, edited by M. Kneissl, Deutsche Geodätische Kommission bei der Bayrischen Akademie der Wissenschaften, Reihe A, Heft 10 a, pp. 1–3, 1954.

"Über die Längen- und Zeitbestimmung bei einer absoluten Schweremessung mit dem Fadenpendel" (Absolute Determination of Gravity with a Simple Pendulum by Measurements of Length and Time), Dr. A. Graf; ibid., pp. 21–31.

These two papers report preliminary considerations of a proposed instrumentation for the absolute determination of g from basic measurements of length and time with a simple pendulum. An accuracy of one milligal is anticipated.

While Berroth discusses the philosophical and theoretical part of the problem, such as the absolute character of the results, Graf is more interested in the technical aspect and presents semitechnical sketches of the apparatus and its significant parts. His paper gives a short review of the older absolute measurements and shows the advantage of the "simple pendulum" type as compared with the mechanically much more complicated reversible pendulum.

It is interesting to learn that old gravity determinations, obtained with simple-pendulum type instruments, come much closer to the modern value than the well-known Potsdam value obtained by Kühnen and Furtwängler by means of a reversible pendulum in 1904.

Both length and time measurements have to be performed with an accuracy of 10^{-5} percent so that the absolute accuracy of about $\pm$one milligal in the resulting value may be obtained. At present, length measurements pose much more difficult problems than time measurements, which, due to recent progress in clocks and registration instruments, can achieve the required accuracy without serious difficulties. Four different ways of changing the distance between the center of suspension and the center of oscillations are suggested without indicating which may be the most promising.

Appreciable errors are caused by minute imperfections, such as an elliptic shape of the path of the pendulum with the minor axis as little as 1/10 millimeter.

The instrument itself is in its preliminary stages of development and therefore, since many obstacles still must be overcome, wooden models instead of much more expensive metal models are being used for test purposes.

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Tables of Hyperbolic Sines and Cosines. National Bureau of Standards Applied Mathematics Series 45, Issued November 15, 1955, Superintendent of Documents, Government Printing Office, Washington 25, D. C. (55 cents).

The Table gives values of $\sinh x$ and $\cosh x$ for $x = 2 - (.001) - 10$ to 9 significant digits, i.e., up to the point where $\frac{1}{2}e^x$ is a sufficient approximation. For 9.5 values, this is adequate extension of Applied Mathematics Series 36. Interpolation formulas for obtaining full accuracy are given in the Introduc-

tion. Used as a supplement to Applied Mathematics Series 36, this Table completes the 9S tabulations of hyperbolic sines and cosines. Mechanically, the arrangement of the tables is excellent. The type is sufficiently large and well spaced to be read easily. Identification of range of x at the top or bottom of each page would have made the tables more easily usable.

D. R. SHREVE
The Carter Oil Company
Tulsa, Oklahoma.

Atlas of Paleogeographic Maps of North America, Charles Schuchert (1858–1942), with introduction by Carl O. Dunbar and index. John Wiley & Sons Inc., New York. 177 pp. $4.75.

Through the good offices of Clara M. LaVerne, formerly secretary to Doctor Schuchert, and of Carl Dunbar, his associate on the Yale University faculty, this set of 84 paleogeographic maps has been selected from the unfinished work-maps of Schuchert and prepared for publication. No change has been made in the interpretations which Schuchert left at his death in October, 1942, since the editors felt that any alterations or additions might distort some of the author's concepts.

His maps have been re-drafted in a uniform manner and are printed on heavy paper, bound with a spiral metal binder that permits the user to lay the volume flat, with a paleogeographic map ($9\frac{3}{4}'' \times 7''$) on the right page and the accompanying legend on the left page. There is no text but an index of formations follows the maps, which begin with Lower Cambrian and are consecutive by significant steps to the highest Cenozoic-Pleistocene. They make a valuable reference for basic geological information and will be useful to all students of, and workers in, the fields of earth science.

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PUBLICATIONS RECEIVED

American Journal of Science, v. 253, nos. 10, 11 & 12 (Oct., Nov. & Dec., 1955)
Annales de Geophysique, v. 11, no. 3 (1955)
Annali di Geofisica, v. 8, no. 3 (July, 1955)
Beihefte zum Geologischen Jahrbuch, v. 19 (July, 1955)
Bulletin of the Earthquake Research Institute, "Supplementary Part" (Oct. 1955),
Bulletin of the Geographical Survey Institute, v. 4, no. 2 (March, 1955)
Bulletin d'Information de l'U.G.G.I., v. 3, nos. 7 & 8 (Sept. & Dec., 1954); v. 4, no. 11 (Sept., 1955
Bulletin of the Research Council of Israel, v. 5-B, no. 1 (Sept., 1955); v. 5-*A*, no. 1 (Nov., 1955)
Bulletin of the Seismological Society of America, v. 45, nos. 3 & 4 (July & Oct., 1955)
Deutsche Hydrographische Zeitschrift, v. 8, no. 2 (1955)
Economic Geology, v. 50, no. 8 (Dec., 1955)
Erdol und Kohle, v. 8, nos. 10, 11 & 12 (Oct., Nov. & Dec., 1955)
Geological Abstracts, v. 3, no. 4 (Dec., 1955)
Geophysical Abstracts, v. 162 (July to Sept., 1955)
Geophysical Notes, v. 8, no. 1 (1955)
Geophysical Prospecting, v. 3, no. 4 with Supplement (Dec., 1955)
Gerlands Beitrage Zur Geophysik, v. 65, no. 1 (1956)
Journal of the Academy of Science USSR, Series Geophysical, nos. 5 & 6 (1955)
Journal of Geophysical Research, v. 60, no. 4 (Dec., 1955)
Journal of Petroleum Technology, v. 8, no. 1 (Jan., 1956)
Journal of the University of Moscow, nos. 6, 8 & 9 (1955)
Mining Engineering, v. 7 nos. 11 & 12 (Nov. & Dec., 1955); v. 8, no. 1 (Jan., 1956)
Petroleum Economy USSR, nos. 10 & 11 (1955)
Proceedings of the Cambridge Philosophical Society, v. 51, no. 4 (Oct., 1955)
Quarterly Journal of the Geological Society of London, v. 111, no. 442 (Nov., 18, 1955)
Rocznik, v. 24, no. 1 (1954)
Science, v. 122, nos. 3175–3183; v. 123, nos. 3184–3187
Science Reports of the Tohoku University, 5th Series, Geophysics, v. 7, no. 2 (Nov., 1955)
Scientific Monthly, v. 81, no. 6 (Dec., 1955); v. 82, nos. 1 & 2 (Jan. & Feb., 1956)
South Australia Department of Mines—Mining Review, no. 98 (June 30, 1953); no. 4 (1955)
Soviet Physics JETP, v. 1, nos. 1 & 2 (July & Sept., 1955)
Tellus, v. 7, nos. 3 & 4 (Aug. & Nov., 1955)
Transactions American Geophysical Union, v. 36, nos. 5 & 6 (Oct. & Dec., 1955)

DISCUSSIONS AND COMMUNICATIONS

LETTER TO THE EDITOR

In 1948 modeling programs for the study of electromagnetic prospecting systems, and for the study of problems in the propagation of elastic waves in inhomogeneous media were initiated at the Institute of Geophysics, University of California, under the support of a group of oil and mining companies. Recently, an enlarged group consisting of about a dozen oil and geophysical service companies has offered support for an associated program in seismic modeling and in seismic wave theory which has as its special objective the experimental and theoretical investigation of seismic scattering and diffraction phenomena. Through the agency of an Advisory Committee consisting of both the project personnel and a representative of each of the participating companies, the project will receive the collaboration of the research staff of the individual companies offering support. The following companies comprise the group now sharing the support of this program:

1. Amerada Petroleum Corp.
2. Atlantic Refining Co.
3. Cities Service Oil Co.
4. Continental Oil Co.
5. Gulf Research Corp.
6. Magnolia Petroleum Co.
7. Phillips Petroleum Co.
8. Shell Development Co.
9. Stanolind Oil and Gas Co.
10. Sun Oil Company
11. The Texas Company
12. Texas Instruments Inc.—Geophysical Service Inc.

In recognition of the possibility that other companies may desire to participate, we are giving notice to the effect that full participation in the project is open at any time to all interested companies.

Further information may be obtained by addressing L. B. Slichter, Institute of Geophysics, University of California, Los Angeles 24, California.

LOUIS B. SLICHTER
Director, Institute of Geophysics
University of California at Los Angeles

MEMORIAL

FRANK MORRIS COWELL

On October 11, 1953 Frank Morris Cowell died at St. John's Hospital in Tulsa after an extended illness. Burial was at Oklahoma City. With his passing the geophysical industry lost one of its most promising younger geophysicists, and his going is deeply mourned by his many friends.

Frank was born in Wichita, Kansas, on August 22, 1918. Subsequently his family moved to Enid, Oklahoma, where he attended grade school and high school. In 1936 he entered the University of Oklahoma and received his Bachelor of Arts degree in 1941.

In September 1942, the war interrupted Frank's studies in the graduate school at Oklahoma University, where he was a lecturer, and he entered the army as a First Lieutenant in the artillery. He served with the army as Reconnaissance Officer, in which capacity he observed and directed artillery fire, and saw combat activity in Normandy, the Rhineland, the Ardennes, and Germany. Much of his duty involved aerial reconnaissance from light aircraft. Later he served as Motor Transport Officer. He was separated from the army in December 1945, but maintained a reserve commission thereafter.

In January 1946 Frank joined Seismograph Service Corporation as a trainee computer. After working in the states during 1946 as computer, he went to Bogota, Colombia, in December of that year and spent the next two years there and in Venezuela. After returning to the United States in 1949 he was placed in charge of a seismic crew, working in the Illinois Basin and later in West Texas and New Mexico.

In October 1951 Frank went north where he served as Party Chief in Alberta and Saskatchewan. On completion of this tour of duty, he stayed only a few months in this country, and in the summer of 1953 went to Mexico to operate a seismic crew. The following year he was again in Colombia.

It was while in Bogota that Frank became ill, and in February 1955 he returned to this country for medical treatment.

Frank Cowell, in addition to being an accomplished geophysicist, had an abounding interest in literature and the arts. His travels to various countries in performance of his work were a source of much pleasure to him, and he seized the opportunity to familiarize himself with the many cultural aspects of each country in which he lived.

Frank is survived by his wife, Vivian June Cowell, and his mother, Mary Etta Degler Cowell. He was an associate member of the American Association of Petroleum Geologists and an active member of the Society of Exploration Geophysicists.

R. W. MOSSMAN

December 27, 1955.

MEMORIAL

FLORENCE ROBERTSON

Florence Robertson died in Wichita Falls, Texas, on November 18, 1954 after an illness of several months with lymphatic cancer.

She was born in Paris, Texas, November 11, 1909. Florence's father died while she was still quite young. Her mother remarried but the only child of this second marriage died of diptheria while the family was living at the old homestead near Windom, Texas and not long afterward her mother also passed away.

She attended high school in Bonham, Texas, graduating in 1927. She graduated from junior college in Paris, Texas, in 1929 and later enrolled in Texas Technological College in Lubbock, Texas, where she received a Bachelor of Arts degree with a major in mathematics and a minor in education in 1935. The following year she recieved a Master of Arts degree from the same institution in physics and mathematics with a geophysical thesis. During the summer of 1936 she taught as an instructor in physics at Texas Technological College.

In the fall of 1936 she entered the Graduate School of Saint Louis University as a graduate fellow in geophysics. She received a Doctor of Philosophy degree in geophysics with minors in physics and mathematics from Saint Louis University in 1945.

She began teaching at Saint Louis University as an instructor in the Department of Geophysics in 1939. With the founding of the Institute of Technology in 1944 she took an active part in the development of the curriculum in geophysical engineering. She was made an assistant professor in 1945, an associate in 1948, and a full professor in 1951.

Doctor Robertson was active in professional and scientific societies. She was a member of the Society of Exploration Geophysicists, the American Institute of Mining and Metallurgical Engineers, the Seismological Society of America which she served as Secretary, Vice Chairman, and Chairman of its Eastern Section. She held the office of Secretary of the Section of Seismology of the American Geophysical Union and was an active member of the Executive Committee of the Union. She was a Fellow of the American Physical Society and the Geological Society of America. She was a member of Pi Mu Epsilon, the Society of Sigma Xi, and the American Society for Engineering Education.

Her untimely death at the age of forty-five at the height of her professional career is a great loss not only to her friends and associates but to the earth sciences and geophysical engineering. The many students who studied geophysics under her guidance and who are now practicing their profession in industrial applications throughout the world are testimony of her effective contribution to geophysical education.

Ross R. Heinrich

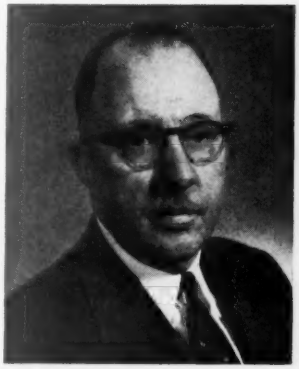
December 28, 1955.

CONTRIBUTORS

A. R. CLARK was born July 1, 1905 in Shelburne, Ontario. He received a B.Sc. degree from the University of Saskatchewan in 1932 and an M.Sc. degree from the same institution in 1934. While working toward the M.Sc. degree he was technician at the radon plant of the Saskatchewan Cancer Commission. In 1939 he received a Ph.D. degree from the University of Toronto.

Dr. Clark was Chief Geophysicist for several Canadian mining and exploration companies until 1946 when he joined the staff of the University of British Columbia as Associate Professor of Physics. He has published technical papers on diffusion, liquid helium, and electric and electromagnetic methods of geophysical exploration.

Dr. Clark is a member of the Society of Exploration Geophysicists, the Canadian Institute of Mining and Metallurgical Engineers, the American Geophysical Union, and the British Columbia Academy of Science.



A. R. CLARK

ERIC W. CARPENTER

ERIC W. CARPENTER was born in Nuneaton, Warwickshire, England, in 1931. He received his early education at King Edward VI School, Nuneaton, before proceeding to the University of Leeds where he entered the Department of Physics in 1949. In 1950 he was awarded the title of Senior Scholar and in 1952 graduated with Honours in Physics. After carrying out work on the electrical resistivity method of geophysical prospecting in the Department of Mining at Leeds, he was awarded the degree of Doctor of Philosophy in 1955. Dr. Carpenter is now employed by the United Kingdom Atomic Energy Authority as a Scientific Officer at an Atomic Weapons Research Establishment.

DARRELL S. HUGHES

DARRELL S. HUGHES received his A.B. in physics in 1926 and his M.S. in physics in 1928 from the University of Kentucky. He received his Ph.D. in physics from the University of Chicago in 1931. From 1931 to 1933 he was a National Research Fellow working at the California Institute of Technology at Pasadena, California. He was employed by the Kittleman North Dom Association until 1935, when he accepted a position as geophysicist with the Shell Oil Company. In 1945 he was appointed Professor of Physics at the University of Texas.

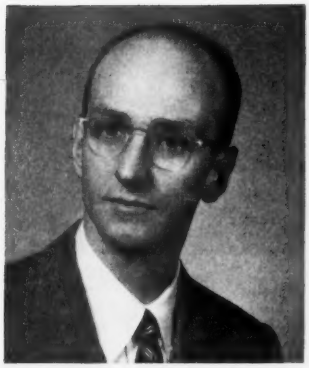
Dr. Hughes is a member of the American Physical Society, Society of Exploration Geophysicists, American Geophysical Union, and the Geological Society of America.

HANS P. LAUBSCHER received a Ph.D. degree in geology from the University of Basel, Switzerland, in 1947. Since 1948 he has been working for Socony Mobil Oil Company de Venezuela, mostly on seismic interpretations.

HANS P. LAUBSCHER

CHRISTIAN MAURETTE

CHRISTIAN MAURETTE was born in Toulouse, France, in 1930. He finished his *Lycee* studies in 1949, graduating with the *Baccalaureat es Sciences* and a General Mathematics grade from the University of Toulouse. During the following two years he attended the courses of the Advanced Mathematics section of *Louis-le-Grand* College in Paris. Then, in 1951 he entered the engineering school *Ecole Centrale de Paris* from which he obtained the Engineering Diploma in 1954. He came to this country in August 1954, on a two-year fellowship sponsored by the Organization of European Economic Co-operation and the International Cooperation Administration to do research in the Physics Department of The University of Texas.



EDWARD TITUS MILLER

EDWARD TITUS MILLER received B.S. degree in Physics from the Massachusetts Institute of Technology in 1949, and the M.A. and Ph.D. degrees in geophysics from Columbia University in 1952 and 1955 respectively. An interest in geophysics was aroused in 1948 by summer employment doing marine research under Dr. Maurice Ewing. From 1949 to 1950 he helped start the Columbia University Geophysical Field Station at Bermuda. From 1950 to 1955 he was a graduate student at Columbia University and a research assistant and later research associate at the Lamont Geological Observatory. This work has included gravity-meter instrumentation, marine seismic studies, and specialized sonar instrumentation but has mainly been on geomagnetic problems. Since 1952 he has been responsible for a program of research on the earth's magnetic field over marine areas.

Dr. Miller is a member of American Geophysical Union, Society Exploration Geophysicists, and Society of the Sigma Xi.

This spring Dr. Miller joins the Geophysics Research Division of the Humble Oil and Refining Company.

LOUIS C. PAKISER, JR.

LOUIS C. PAKISER, JR., received the degree of Geological Engineer from the Colorado School of Mines in 1942. He served as Junior Geophysicist with The Carter Oil Company from 1942 to 1943 and Geophysical Computer from 1946 to 1949. He was on military leave from 1943 to 1945, serving in an Army topographic mapping unit. In 1949 he accepted the position of National Executive Director of the American Veterans Committee and served in that capacity until 1952. Mr. Pakiser has been serving as a Geophysicist with the U. S. Geological Survey since 1952, with whom he is now Chief of the Ground Surveys Section of the Geophysics Branch.

Mr. Pakiser is a member of the Society of Exploration Geophysicists and the American Association of Petroleum Geologists.

FRANK PRESS is presently Professor of Geophysics at the California Institute of Technology. He was formerly Associate Professor at Columbia University where he took his Ph.D. in 1949. His main interests have been the theoretical and experimental study of elastic wave propagation in layered media; and the geophysical investigation of crustal structure.

FRANK PRESS

GEORGE SHUMWAY

GEORGE SHUMWAY, received the B.S. in geology from Massachusetts Institute of Technology in 1951 and B.A. from Middlebury College in 1951 also, having participated in the 5-year Combined Plan of study. He received the M.S. in geology from M.I.T. in 1951. Since 1951 he has been employed in the Sea Floor Studies Section of the U. S. Navy Electronics Laboratory in San Diego, as marine geologist and oceanographer. He has done graduate work in oceanography at the Scripps Institution of Oceanography on a part time basis since 1951. In 1953 he helped start a service company, Geological Diving Consultants, Inc. which performs underwater geological mapping and engineering studies.

Mr. Shumway is a Member of SEG, American Geophysical Union, Geological Society of America, American Assoc. Petroleum Geologists, and associate member Sigma Xi.

MARK K. SMITH

MARK K. SMITH obtained his undergraduate training at the Massachusetts Institute of Technology, at the University of California at Los Angeles, and at the University of Colorado, majoring in physics and geophysics. He received a B.S. degree in Geophysics in 1951 and a Ph.D. degree in Geophysics in 1954 from M.I.T. During 1953 he worked with the Geophysical Analysis Group at M.I.T., and in 1954 joined Geophysical Service Inc. in Dallas, Texas, as a Research Seismologist. He is now Director of Seismic Research for G.S.I.

Dr. Smith is a member of the Society of Exploration Geophysicists and the Dallas Geological and Geophysical Societies.

W. J. TOULIS

W. J. TOULIS received his B.S. and M.S. degrees in Electrical Communications Engineering from the Massachusetts Institute of Technology in 1940 and his Ph.D. degree in Physics from the University of California at Berkeley in 1950. Briefly, his background is broad and varied: (a) The development of high frequency circuits and directional propagation devices at RCA, (b) the decomposition of water by high energy rays and particles at the University of California, and (c) the acoustic properties of matter at the U. S. Navy Electronics Laboratory in San Diego.

He is a member of The Society of the Sigma Xi, The American Physical Society, and The Acoustical Society of America.

JAMES R. WAIT

JAMES R. WAIT was born in Ottawa in January, 1924. He attended McGill University for a brief period before enlisting in the Canadian Army in 1942. By the end of the war he was in charge of a radar maintenance group at Kingston, Ontario.

He received the B.A.Sc. and M.A.Sc. degrees in Engineering Physics from the University of Toronto in 1948 and 1949 respectively. At this time he was employed as a junior research engineer at the Hydro Electric Power Commission of Ontario where he assisted in the development of an infra-red bolometer. Returning to further graduate work to the University of Toronto, he obtained a Ph.D. degree in electromagnetic theory in 1951.

From 1949 to 1952 Dr. Wait was associated with Newmont Exploration Limited of Jerome, Arizona where he conducted theoretical and experimental research in electrical prospecting. From 1952 to 1955 he was a section leader

in the Defence Research Telecommunications Establishment in Ottawa where he was mainly concerned with theoretical problems in radiation. At present he is a consulting theoretical physicist to the Radio Propagation Engineering Division of the National Bureau of Standards in Boulder, Colorado.

RICHARD E. WARRICK

RICHARD E. WARRICK received a B.S. degree in Physical Science from Stanford University in 1951.

He was employed by Stanford Research Institute as a seismic observer from 1951 to 1953. Since 1953, he has been a geophysicist with the Ground Surveys Section, Geophysics Branch of the U. S. Geological Survey.

Mr. Warrick is a member of the Society of Exploration Geophysicists and the European Association of Exploration Geophysicists.

SULHI YÜNGÜL was born in Turkey in 1919. He received his B.S. in Mining Engineering from the Montana School of Mines in 1943, his M.S. in Geological Sciences (Geophysics) in 1944 and Geophysical Engineer's degree in 1945, both from the California Institute of Technology.

He was employed from 1945 to 1952 by M.T.A. Enstitüsü of Turkey, as party chief, supervisor and chief geophysicist, from 1952 to 1954 by Etibank of Turkey as chief geophysicist. At present he is employed by California Research Corporation, La Habra, California, as research geophysicist.

SULHI YÜNGÜL

Biographies and photographs of the following authors may be found in recent issues of GEOPHYSICS: MILTON B. DOBRIN, v. 17, p. 992; KARL DYK, v. 18, p. 480 (see Society Round Table this issue); G. M. HABBERJAM, v. 17, p. 158; GEORGE P. SARRAFIAN, v. 20, p. 966; J. P. WOODS, v. 17, p. 416.

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(CHARTERED FEBRUARY 2, 1948)

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1st Vice-President: STANLEY WILCOX, Seismograph Service Corp., Box 1590, Tulsa 1, Okla.
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Secretary: JOHN RUPNIK, Consultant, Jenkins Bldg., Tulsa, Okla.
Treasurer: J. E. BONDURANT, Phillips Petroleum Co., Bartlesville, Okla.
Editor: E. V. MCCOLLUM, E. V. McCollum & Co., 515 Thompson Bldg., Tulsa, Okla.
District Representatives:
NORMAN RICKER ('56), The Carter Oil Co., Box 801, Tulsa, Okla.
W. T. BORN, Geophysical Research Corp. ('56), 2607 N. Boston Pl., Tulsa, Okla.
L. Y. FAUST ('57), Amerada Petroleum Corp., Box 2240, Tulsa, Okla.
Meetings: Monthly, 2nd Thursday, 7:00 P.M., meeting only, University of Tulsa, Room 224, Petroleum Science Hall

SOCIETY OF EXPLORATION GEOPHYSICISTS HOUSTON SECTION

(CHARTERED FEBRUARY 14, 1948)

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1st Vice-President: J. F. FREEL, Research Exploration, Inc., Box 13275, Houston 8, Texas
2nd Vice-President: JOHN BYERS, States Explorations Co., 709 M&M Bldg., Houston, Texas
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District Representatives:
O. T. LAWHORN ('57), Pan American Production Co., 1223 Esperson Bldg., Houston, Texas
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Meetings: Monthly, 1st Monday, Noon luncheon ($1.50), Rice Hotel.

PACIFIC COAST SECTION

(CHARTERED APRIL 12, 1948)

President: T. P. ELLSWORTH, Geophysical Service Inc., Bakersfield, Calif.
Vice-President Northern District: PAUL F. CLEMENT, Western Gulf Oil Co., Bakersfield, Calif.
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President: JOHN A. LESTER, Magnolia Petroleum Co.
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O. C. CLIFFORD, JR., The Atlantic Refining Co., Box 2819, Dallas 1, Texas
CECIL H. GREEN, Geophyscial Service Inc., 5900 Lemmon Ave., Dallas 9, Texas
J. P. WOODS, The Atlantic Refining Co., Box 2819, Dallas 1, Texas
Meetings: Monthly, generally but not invariably 2nd Monday (contact any member). 8:00 P.M. Fondren Science Bldg., S.M.U.

FORT WORTH GEOPHYSICAL SOCIETY

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District Representatives:
FRANK MORTLOCK, Gulf Oil Corp., Drawer 1290, Ft. Worth 1, Texas
L. O. SEAMAN, Sinclair Oil and Gas Co., 901 Fair Bldg., Ft. Worth, Texas
Meetings: Monthly, 4th Monday, Noon Luncheons ($1.50), Texas Hotel.

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Secretary-Treasurer: HERBERT J. FERBER, Gulf Oil Corp., Box 1731, Shreveport, La.
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B. B. BURROUGHS, Sunray Oil Corp., Ricou-Brewster Bldg., Shreveport, La.
Meetings: Monthly, normally last Monday, Noon Luncheon ($1.50), Captain Shreve Hotel, Shreveport.

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Secretary: MALCOLM KNOCK, Stanolind Oil and Gas Co.
Treasurer: R. J. KNOTT, The Atlantic Refining Co.
Meetings: Monthly, 2nd Tuesday 7:30 P.M., free coffee and doughnuts, Cowden Jr. High School cafeteria, Midland, Texas.

DENVER GEOPHYSICAL SOCIETY

(CHARTERED MAY 19, 1950)

President: E. B. WASSON, Cosden Petroleum Co., 1510 Denver Club Bldg., Denver, Colorado
Vice-President: C. E. RIDDEL, Consultant, Denver, Colorado

Secretary-Treasurer: J. E. THOMPSON, Sun Oil Co., Box 1798, Denver, Colorado
District Representative: C. C. O'BOYLE, Brainerd & Van Tuyl, 232 Empire Bldg., Denver, Colorado
Meetings: Monthly, 1st Monday, 5:30 P.M., meeting only, Petroleum Club.

CANADIAN SOCIETY OF EXPLORATION GEOPHYSICISTS

(CHARTERED JANUARY 24, 1952)

President: R. B. ROSS, Canadian Gulf Oil Co., Box 130, Calgary, Alberta
Vice-President: G. J. BLUNDUN, Home Oil Co., 304 6th Avenue W, Calgary
Secretary-Treasurer: DON V. BIGELOW, Mobil Oil of Canada, Ltd., Mobil Oil Bldg., Calgary
District Representatives: F. G. COOTE, Accurate Exploration Ltd., 2201 10th Ave. W., Calgary, Alberta; F. A. HALE, Calif. Standard Co., Medical Arts Bldg., Calgary.
Meetings: (Data not received)

GEOPHYSICAL SOCIETY OF OKLAHOMA CITY

(CHARTERED SEPTEMBER 30, 1952)

President: J. E. STONES, The Superior Oil Co., 2211 Liberty Bank Bldg., Oklahoma City, Okla.
1st Vice-President: R. D. ROBERTS, Sohio Petroleum Co., Box 3656, Oklahoma City, Okla.
2nd Vice-President: D. J. VAN NOSTRAND, Gulf Oil Corp., Box 9667, Oklahoma City, Okla.
Secretary: JOHN BEMROSE, Sohio Petroleum Co., Box 3656, Oklahoma City, Okla.
Treasurer: R. H. PEACOCK, Superior Oil Co., 2211 Liberty Bank Bldg., Oklahoma City, Okla.
District Representative: R. D. ROBERTS, Sohio Petroleum Co., Box 3656, Oklahoma City, Okla.
Meetings: Monthly, 2nd or 3rd Monday, time and place to be announced.

CASPER GEOPHYSICAL SOCIETY

(CHARTERED MAY 23, 1953)

President: G. NEWMAN SHELL, Cities Service Oil Co., 1719 S. Oak, Casper, Wyo.
Vice-President: GEORGE N. MEADE, Stanolind Oil & Gas Co., Box 40, Casper, Wyo.
Secretary-Treasurer: WESLEY N. FARMER, Richfield Oil Corp., Box 698, Casper, Wyo.
District Representative: HOMER ROBERTS, Petty Geophysical Engineering Co., Box 651, Casper, Wyoming
Meetings: Monthly, 1st Monday, 7:00 P.M., Dinner ($2.75), Townsend Hotel

GEOPHYSICAL SOCIETY OF SOUTH TEXAS

(CHARTERED NOVEMBER 9, 1953)

President: WELDON L. CRAWFORD, Petty Geophysical Engineering Co., Transit Tower, San Antonio, Texas
Vice-President: LEE MOORE, Petty Geophysical Engineering Co., Transit Tower, San Antonio, Texas
Secretary-Treasurer: LAWTON B. STEPHENSON, Petty Geophysical Engineering Co., Transit Tower, San Antonio, Texas
Distric Representative: BART PRATT, Petty Geophysical Engineering Co., Box 2061, San Antonio, Texas
Meetings: Semi-monthly, 2nd and 4th Wednesdays, Noon luncheon (Cafeteria style), Sommers Cafeteria, Main Plaza, San Antonio.

SOUTHEASTERN GEOPHYSICAL SOCIETY

(CHARTERED APRIL 1, 1954)

President: JOHN F. BOYD, Tidelands Exploration Co., New Orleans
Vice-President: O. G. HOLEKAMP, Shell Oil Co., New Orleans
Secretary-Treasurer: R. E. HALSEY, Sinclair Oil & Gas Co., New Orleans

District Representatives:
L. W. COBENA, The Texas Co., New Orleans
M. G. FREY, The California Co., New Orleans
Meetings: Monthly, 3rd Monday, Noon luncheon ($1.50), St. Charles Hotel, New Orleans.

MONTANA GEOPHYSICAL SOCIETY

(CHARTERED APRIL 12, 1954)

President: SAM MARSH, The Carter Oil Co.
1st Vice-President: JACK PETERS, Mobil Producing Co.
2nd Vice-President: M. D. WICKERHAM, Gulf Oil Corp..
Secretary-Treasurer: C. F. MOORE, Sohio Petroleum Co.
District Representative: THOMAS C. KING, Murphy Corp.
Meetings: Monthly, Second Monday.

DAKOTA GEOPHYSICAL SOCIETY

President: W. E. PHILLIPS, Stanolind Oil & Gas Co., Box 1437, Bismarck, N. D.
1st Vice-President: HUGH MCCAIN, The Atlantic Refining Co., Box 1076, Bismarck, N. D.
2nd Vice-President: QUIN HAYES, Mobil Producing Co., Box 1236, Bismarck, N. D.
Secretary-Treasurer: R. R. PHAIR, Roundup Powder Co., Box 452, Bismarck, N. D.
District Representative: HENRY NOGAMI, The Atlantic Refining Co., Box 728, Dickinson, North Dakota
Meetings: Monthly, 1st Friday, 7:30 P.M., Petroleum Club, Prince Hotel, Bismarck.

JACKSON GEOPHYSICAL SOCIETY

(CHARTERED MAY 12, 1955)

President: PHIL P. GABY, Delta Exploration Co., 206 Rankin St., Jackson, Miss.
Vice-President: FRED FORWARD, Phillips Petroleum Co., Box 3540, Jackson, Miss.
Secretary-Treasurer: W. J. ROBINSON, Sinclair Oil & Gas Co., Box 99, Jackson 5, Miss.
District Representative: BRYAN A. DUBY, The Carter Oil Co., Box 1490, Jackson, Miss.
Meetings: Monthly, during third week, 5:30–6:30 refreshments, 6:30–7:30 dinner ($2.00), technical meeting to follow, Roof Garden of Robert E. Lee Hotel, Jackson, Mississippi.

SOUTHWEST LOUISIANA GEOPHYSICAL SOCIETY

Lafayette, Louisiana

(CHARTERED JANUARY 4, 1956)

President: J. J. SCHNEIDER, JR., Sohio Petroleum Co., Box 1090, Lafayette, La.
1st Vice-President: E. L. RICKETTS, Forest Oil Corp., Box 1401, Oil Center Sta., Lafayette, La.
2nd Vice-President: E. L. CURRENT, Cities Service Oil Co., Box 1407, Oil Center Sta., Lafayette, La.
Secretary-Treasurer: J. W. BELL, JR., Pan-Amer. Prod. Co., Drawer 1409, Oil Center Sta., Lafayette, La.
District Representatives:
E. L. RICKETTS, Forest Oil Corp.
P. H. JEFFERS, Chemical Service Inc.

STUDENT SOCIETIES

(AFFILIATED)

COLORADO SCHOOL OF MINES SOCIETY OF STUDENT GEOPHYSICISTS

Golden, Colorado

President: RONALD E. DIEDERICH
Vice-President: ROGER C. GORE
Secretary-Treasurer: ROBERT I. BUCKNELL
Faculty Sponsor: JOHN C. HOLLISTER
Meetings: (Data not received)

GEOPHYSICAL SOCIETY OF SAINT LOUIS UNIVERSITY

President: RICHARD SNEIDER
Vice-President: GILBERT BOLLINGER
Secretary: THOMAS MCEVILLY
Treasurer: ROBERT RILEY

Faculty Moderator: (To be appointed)

Meetings: Monthly, 2nd Wednesday, 7:30 P.M., Meeting only, Institute of Technology.

SOCIETY OF EXPLORATION GEOPHYSICISTS HOUSTON STUDENT SECTION

President: TOM VINING, University of Houston
1st Vice-President: D. E. MILLER, Rice Institute
2nd Vice-President: EUGENE GREEN, University of Houston
Treasurer: JACK WRIGHT, University of Houston
Secretary: D. H. COOK, University of Houston
University of Houston Sponsor: DR. R. A. GEYER, Geophysical Service Inc., Box 6037, Houston 5, Texas
Rice Institute Sponsor: DR. CHARLES B. OFFICER, JR.
Meetings: (Data not received)

UNIVERSITY OF TORONTO GEOPHYSICAL SOCIETY

President: DOUGLAS W. ALLAN
Vice-President: JOHN JAMIESON
Secretary-Treasurer: JOHN E. HOGG
Faculty Sponsor: PROF. J. A. JACOBS
Meetings: Bi-weekly, alternate Thursdays, 4:00 P.M., 49 St. George St.

UNIVERSITY OF TULSA STUDENT GEOPHYSICAL SOCIETY

TRANS-PECOS STUDENT SECTION

Box 56, Texas Western College
El Paso, Texas

President: JOE H. SCALES
1st Vice-President: PETER G. GRAY
2nd Vice-President: HARRY R. HIRSCH
Secretary: JOHN T. SAMPLE, JR.
Treasurer: WILLIAM D. GRANT
Faculty Sponsor: WM. S. STRAIN
Meetings: To be announced.

PENNSYLVANIA STATE UNIVERSITY GEOPHYSICAL SOCIETY

College of Mineral Industries
University Park, Pennsylvania

President: JOHN K. LYON
Vice-President: HAROLD G. ROZELLE
Secretary: JAMES B. IMSWILER
Treasurer: DONALD W. STRICKLER
Faculty Sponsor: DR. B. F. HOWELL

UNIVERSITY OF UTAH GEOPHYSICAL SOCIETY

College of Mines and Mineral Industries
Salt Lake City, Utah

President: WILLIAM M. DOLAN
Vice-President: J. BURLIN JOHNSON, JR.
Secretary: HOWARD L. CONFER
Treasurer: PETER MANDEL, JR.
Faculty Advisor: DR. KENNETH L. COOK
Meetings: Monthly, 1st Thursday, noon, Mines Bldg.; other special meetings to be announced

GEORGIA INSTITUTE OF TECHNOLOGY GEOPHYSICAL SOCIETY

Box 4748

Atlanta, Georgia

President: WILLIAM S. SCOTT, JR.
Vice President: JAMES E. TUCKER
Secretary-Treasurer: JAMES P. DOWNS
Program Chairman: JUSTIN T. BRADFORD
Faculty Sponsor: DR. H. W. STRALEY III

MEETINGS

TWENTY-FIFTH ANNIVERSARY MEETING

Shirley Savoy Hotel, Denver, Colorado
October 3–6, 1955

Hosts to the first independent annual meeting of SEG were the members of the Denver Geophysical Society, E. B. Wasson, President. Planning and organization were handled by Robert Dyk, General Chairman, and Ralph Holmer, Vice-Chairman. A complete roster of committees appears on page 970 in October 1955 GEOPHYSICS.

In a history of the Society, brought up to date especially for this meeting, President Paul L. Lyons said "Our civilization has become the Age of Petroleum. It is fitting that in the silver anniversary year of the Society of Exploration Geophysicists we pause to give homage to those many scientists who founded exploration geophysics. The history of the Society is closely related to the many firsts in exploration geophysics and its history has here been commingled with the history of the art."

ROBERT DYK
GENERAL CHAIRMAN
25TH ANNUAL MEETING

MARVIN ROMBERG
PROGRAM CHAIRMAN
25TH ANNUAL MEETING

Statistics:

The total registration of 1,502 included 1,073 who paid the $5.00 fee. The one thousandth registrant, Roy G. Quay, 296 ladies, 102 exhibitors, and 31 students, were registered free. A total of 377 attended the luncheon, 299 attended the ladies' luncheon and fashion show, 96 attended the ladies' mountain tour, 624 attended the dance, and 114 went on the field trip.

Program:

An outstanding technical program was prepared by the committee headed by Marvin Romberg, Chairman, John Hollister, Vice-Chairman, and E. B. Wasson. Abstracts of the papers presented appear elsewhere in this issue. Credit is due also to the other members of the Program Committee, and especially to the officers of all the local sections, many of whom contributed directly by participating in special symposia. The technical program continued from Monday noon, October 3, until Thursday evening, October sixth.

Special guests appearing in the opening session were Lt. Governor Stephen L. R. McNichols of Colorado and former Governor Dan Thornton. Mr. McNichols welcomed the Society to Colorado and gave credit to geophysicists for " . . . 'opening up' our oil fields. More recently your activities in the field of uranium exploration have been of great benefit," he added. Mr. Thornton, who issued the

Technical session, 25th Annual Meeting. This picture was taken as G. M. Knebel, President of the AAPG, presented his paper, "Some of the habitats of oil."

invitation to the Society some 18 months earlier, praised the geophysicists' role in national defense and in developing the nation's high standard of living. "You can take great satisfaction," Thornton said, "in contributing to a better way of life, to keeping America strong, through your training, knowledge and integrity."

The Society's historic ties with The American Association of Petroleum Geologists were further strengthened when G. M. Knebel, SEG member and President of the AAPG, presented his interesting paper, "Some of the habitats of oil." At the close of this paper Mr. Knebel presented President Lyons with a check for $2,100, SEG's share in the margin resulting from the New York "Oil Finders Convention" last March.

In the opening session the address by retiring President Paul Lyons was presented; Milton B. Dobrin, retiring Editor, presented the first annual report for the Research Committee, with Robert Van Nostrand, "Review of current developments in exploration geophysics"; E. A. Eckhardt reported as President of the American Geological Institute; and Sigmund Hammer gave an interim report to midyear for the Standing Committee on Geophysical Activity, as retiring Chairman.

A total of 49 technical papers were presented by 74 contributors, the majority of whom had never before given a paper at an annual SEG meeting. The program and planning committees are indebted to the Robert H. Ray Company for the excellent abbreviated program booklet.

Three special sessions were included in the technical program. The "Symposium on multiple seismometers" presented Tuesday afternoon was sponsored by the Houston Section. The Wednesday evening "Symposium on magnetic recording" was sponsored by the Tulsa Section, and on Thursday evening a full session on uranium exploration was presented.

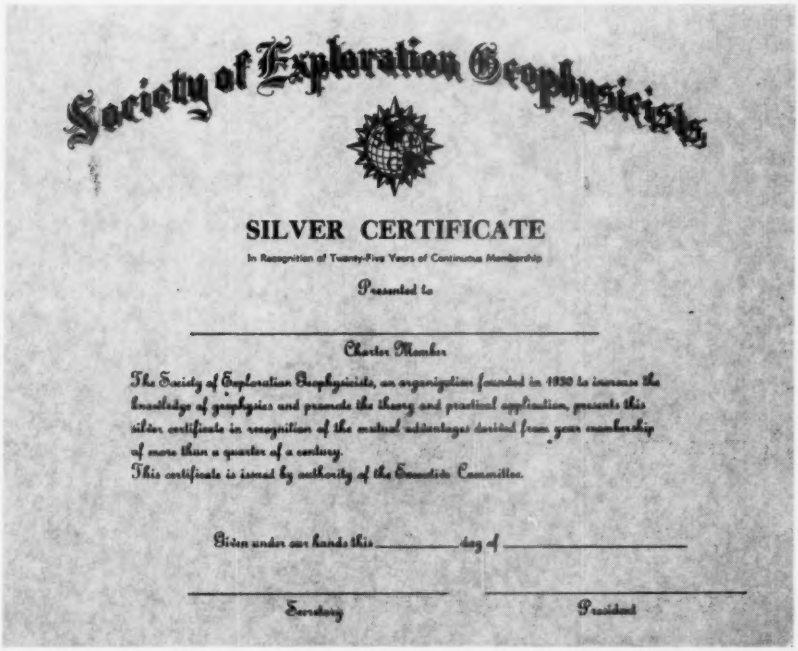
Dan Thornton, former Governor of Colorado, and Lt. Governor Stephen L. R. NcMichols are welcomed by Robert Dyk, General Chairman of the 25th Annual Meeting.

Some of the 377 delegates at the old timers' luncheon during the 25th Annual Meeting.

Social functions:

An "old-timers' luncheon," to which every ticket was sold, honored the past presidents and charter members of the Society. All charter members were awarded certificates denoting 25 years of membership by President Robert C. Dunlap, Jr. Cigarette lighters, engraved "SEG—25th Annual Meeting—Denver 1955," were presented as favors for this luncheon by Kennecott Copper Corporation, and entertainment was provided by "Stutterin' Sam."

The annual dance was followed at midnight Tuesday by breakfast. Music was furnished by the Billy May Orchestra. The ladies' program included the luncheon and fashion show, with members of the SEG Denver Auxiliary as models. The ladies' mountain tour through old Central City and Idaho Springs was highlighted by a stop at Red Rocks amphitheatre, where Dr. L. W. Leroy of Colorado School of Mines gave a popular discussion of the local geology. Luncheon was served at the Willow Springs Country Club. On Wednesday evening a valuable collection of gems was displayed by Professor Paul Keating of the Colorado School of Mines.



Society of Exploration Geophysicists

SILVER CERTIFICATE

In Recognition of Twenty-Five Years of Continuous Membership

Presented to

_____

Charter Member

The Society of Exploration Geophysicists, an organization founded in 1930 to increase the knowledge of geophysics and promote the theory and practical application, presents this silver certificate in recognition of the mutual advantages derived from your membership of more than a quarter of a century.

This certificate is issued by authority of the Executive Committee.

Given under our hands this _____ day of _____

_____ _____

Secretary President

Certificate presented to living Charter Members at the 25th Annual Meeting. The Charter Members are: Donald C. Barton, George M. Bevier, J. P. Black, L. W. Blau, L. G. Christie, D. M. Collingwood, Henry C. Cortes, Donald M. Davis, Alexander Deussen, Hellmut Dorsch, J. Brian Eby, Norbert Gella, J. E. Gunn, E. Helmer Hedstrom, Otto Heidecke, H. Hlauschek, J. O. Hoard, A. I. Innes, W. P. Jenny, F. Kaselitz, John D. LaTouche, R. W. D. LaTouche, O. C. Lester, Jr., Burton McCollum, Chas. Gill Morgan, Dabney E. Petty, O. S. Petty, George Steiner, Kurt F. Ritzau, E. E. Rosaire, H. W. Rose, C. M. Ross, Louis A. Scholl, Jr., J. P. Schumacher, A. L. Selig, Stuart Sherar, Harold Shore, A. L. Smith, Elisabeth Stiles, Gerhard Stubbe, O. F. Sundt, John F. Weinzierl, G. H. Westby, Paul B. Whitney, John H. Wilson, and B. O. Winkler.

Mrs. W. H. Wurth, Mrs. C. L. Barker and Mrs. R. L. Kretz look on as Mr. and Mrs. N. R. Park register for the 25th Annual Meeting.

Television panel, 25th Annual Meeting—Left to right, Robert Dyk, General Chairman, R. C. Dunlap, Jr., President, Paul L. Lyons, retiring President, Sigmund Hammer, past President.

Field Trip:

The Rocky Mountain Association of Geologists presented its well-known field trip along the Front Range foothills west of Denver on Friday following the meeting. Refreshments were furnished along the way by J. D. Buckley, Inc.

Broadcasts and recordings:

The Publicity Committee, through L. F. Lockard, Chairman, and Jason S. Johnson, arranged for two commemorative tape recordings of television and radio programs presented in connection with the meeting. The first recording was taken from a television broadcast on which Paul L. Lyons, R. C. Dunlap, Jr., Sigmund Hammer and Robert Dyk formed a panel, first to introduce geophysics to the public, and second to discuss the presumptuous questions of "How much oil is there left?" and "Will atomic energy replace oil as a power source?" The second recording was made during a radio program consisting of four interviews with SEG members who are active in the Rocky Mountain area. Participants were F. A. Thurman, Jack Knight, Wendell Hawkes and J. S. Johnson. They discussed the supply and demand for oil, the exploration problems involved, and the general influence of these factors in Colorado. Both recordings may be obtained from the SEG Standing Committee on Publicity.

Awards:

Honorary Membership in the Society was conferred upon Cecil H. Green, J. B. Macelwane, S.J., and Paul Weaver in recognition of their outstanding contributions to the science of exploration geophysics. These awards brought to eight the number of living men so honored. The citations appear elsewhere in this issue of GEOPHYSICS. Also at the opening session the awards in the annual student paper contest were announced. First prize went to G. D. McPherson of the University of Toronto for his paper, "New and current methods of age determination—their application to the age of the earth." Second prize was awarded to D. E. Wright of the University of Alberta for his paper, "An aeromagnetic map interpretation."

Exhibits:

A total of 41 companies took part in the commercial exhibit held in connection with the meeting, occupying 48 booths in the Shirley Savoy Hotel plus space in an adjacent outdoor parking area. The meeting committees express their appreciation to these exhibitors whose subscription and cooperation have made possible the success of the Society's first independent annual meeting.

Some of the technical session chairmen for the 25th Annual Meeting. Left to right, back row: W. L. Crawford, Ellis H. Shannon, J. R. Walker, J. M. Crawford, P. H. Gaby, John Mathews, J. E. Stones. Front Row: R. D. Holland, Howard Itten, H. V. W. Donohoo, W. H. Taylor, O. H. Armstrong and J. E. Finley.

EXECUTIVE COMMITTEE, YEAR ENDING NOVEMBER 1, 1956

Left to right, standing: Norman Ricker, Editor; Dave P. Carlton, Vice-President; Paul L. Lyons, Past President; G. A. Grimm, Secretary-Treasurer. Seated, R. C. Dunlap, Jr., President.

Cecil H. Green, right, received the Eighth Award of Honorary Life Membership from George E. Wagoner during the 25th Annual Meeting.

EIGHTH AWARD OF HONORARY MEMBERSHIP

CITATION

Cecil H. Green was born in Manchester, England, in 1900 and came over to Canada at an early age. He attended grammar school and high school in Vancouver, British Columbia, and took a portion of his undergraduate work at the University of British Columbia. He then transferred to the Massachusetts Institute of Technology where he obtained a Master's degree in Electrical Engineering in 1924.

His first position was with the General Electric Company at Schenectady where he served as a development engineer for the A.C. Engineering Division. During this time he also instructed in the G.E. Advanced Engineering Course.

It was on the banks of the Mohawk River that Green met and married Ida Maybelle Flansburgh in 1926. Miss Flansburg little realized at that time what a nomad Green would turn out to be. The awakening came shortly though, and Green left GE to join the Raytheon Manufacturing Company, which an MIT classmate had helped to organize.

With Raytheon, he took part in the development of gaseous tube devices which had important applications in the first batteryless radio receivers.

A love of the West then took the Greens to Palo Alto, California, where Cecil joined the Federal Telegraph Company, a subsidiary of the International Telephone and Telegraph Company. This was a connection which Green enjoyed until the company moved its facilities back to Newark, New Jersey. Although he was in charge of the department devoted to making power transmitting tubes, Green decided against the move.

Another former associate, Roland F. Beers, who had also been an engineer with Raytheon, began telling Green about a new, rather fantastic business of applying physics to geology in the search for oil. Here was an entirely fresh challenge in a new technical field—and besides, it involved work in the wide open spaces. With this in mind the Greens settled down in earnest to this business of moving around, and Cecil joined the newly formed Geophysical Service, Inc., as Chief of Seismic Party 310 at Maude, Oklahoma, in 1930.

W. E. McDermott and Chester J. Donnally were key members of this party, and Ronald J. Cullen client representative of Twin States Oil Company, was the fellow who initiated Green's geological education.

After several years as party chief and then supervisor on various domestic operations, Green was given special assignments which fitted in well with his love for travel. Prior to World War II he fulfilled supervisory assignments in Canada, Colombia, Ecuador, India, Iraq, Saudi Arabia and Sumatra.

In 1941 he was promoted to Vice President and in 1950 he assumed his present duties as President of GSI.

Green has been proud of his Society of Exploration Geophysicists affiliation since the time that he, Fred Romberg, Hewitt Dix, Curt Johnson, Frank Morgan, Gene Vallat and others formed the first geophysical study group in Los Angeles in 1939. He has the distinction of having served on the SEG Executive Committee for four years, starting as Secretary-Treasurer and ending as President of the Society in 1947–1948. As Vice-President, he and Henry Cortes were instrumental in establishing the first permanent office of SEG and employing Colin Campbell as SEG's Business Manager.

Also during his term in office Green greatly encouraged the development of local and student sections in the Society. Green has shown a strong personal interest in education in the field of exploration geophysics.

Together with Dr. Robert R. Shrock of MIT, Green was instrumental in inaugurating, in 1951, a summer cooperative program designed to give selected college students the advantage of an extensive orientation session in applied geophysics and the opportunity of studying geophysics first-hand by performing summer work with a geophysical field party.

To date more than 100 students from colleges and universities across the nation have taken part in the plan. Success of the program in the United States prompted the establishment, in 1952, of a similar plan in Canada. The Canadian plan was set up with the help of Dr. J. Tuzo Wilson of the University of Toronto.

Green has long maintained that geophysics is an art as well as a science, and, being an art, it is very dependent upon people. In inaugurating the student plan Green went on the theory that a person can *watch* an expert for years without becoming expert on anything but watching.

In recognition of his strong personal interest in education in the field of exploration geophysics and for service to the industry in general, he was presented with an honorary Doctor of Engineering degree from the Colorado School of Mines in 1953.

Cecil, it gives me great pleasure to present to you, on behalf of the Society of Exploration Geophysicists, this certificate which signifies the highest award that the Society can bestow upon an individual—a Life Honorary Membership.

GEORGE E. WAGONER

NINTH AWARD OF HONORARY MEMBERSHIP

CITATION

A professional society, like a man, is judged by the company it keeps. In this respect the Society of Exploration Geophysicists is indeed fortunate. On this, its Silver Anniversary Meeting, the Society has elected to give public recognition to three of its deserving members who have made important contributions to the development of exploration geophysics and have helped to raise the Society to its present high position in the esteem and respect of its members and of the professional world. I have the high honor to represent the society in presenting an Honorary Life Membership to one of these three at this special 25th Anniversary meeting. The exceptional merit which this award implies is measured by the fact that in the entire history of the Society it has been granted prior to this meeting only seven times.

Father James B. Macelwane, S.J., is a geophysicist who has gained world renown by his researches and writings and by the reflected glory of his many eminent students who have been inspired to greatness by his enthusiastic and sympathetic teaching. He has been an outstanding member of the Society of Exploration Geophysicists for twenty years. His annual surveys of geophysical education which have been published in GEOPHYSICS each year since 1950 have become classics. It is appropriate that the Society should recognize Father Macelwane's distinguished service by awarding to him the highest honor which it has in its power to bestow.

Father Macelwane's contributions to exploration geophysics cover a wide range. Probably foremost is the long list of successful students of geophysics which he has inspired and trained. Among these are such great names as Perry Byerly and Earnest A. Hodgson. In 1925 he organized the first educational Department of Geophysics in the Western Hemisphere. In addition to this teaching, he has made important research contributions of his own and has published about 100 papers and articles, principally on seismology and meteorology. He is the author or co-author of six books on physics and geophysics. His own labors have greatly broadened the horizons of the earth sciences.

Many honors have been conferred upon Father Macelwane. To enumerate them all would be unnecessary and tedious. Those of you who would like to check a partial listing may refer to Pages 54 and 55 in your program booklet. He is a member of the National Academy of Sciences and was appointed by President Eisenhower to a six year term as a member of the National Science Board of the National Science Foundation. He has been chosen by his colleagues for offices of distinction in many scientific societies and is now serving a three year term as president of the American Geophysical Union. He has been awarded the Bowie Medal of the A.G.U. and several honorary Doctors degrees. He has held many important positions at St. Louis University and is now Dean of the Institute of Technology.

Although Father Macelwane is primarily an educational administrator, he has not neglected practical matters. While a young graduate student and teacher at the University of California in Berkeley from 1921 to 1925, he was a consultant in seismic exploration to the late Frank Rieber of subsequent Sonograph fame. His tri-partite micro-seismic detector system is used by the Navy for detecting and tracking storms at sea. In common with many other geophysicists his duties take him on frequent and long trips to all parts of the world. Very appropriately his students have given him

the pseudo-theological title "The Bishop of Tours." On one public occasion, he was presented with a pair of roller skates to help him keep his many appointments. He also has been called an "Earth Quaker" by colleagues who consider it humorous that a Jesuit should be a Quaker. This may, or may not have inspired the title of his popular book "When the Earth Quakes." These intimacies add to the measure of the greatness of the man.

At many celebrations of the 50th Anniversary of Father Macelwane's entry into the Jesuit Order (one of which I had the priviledge to attend) were heard several expressed opinions that the *Order* had good reasons indeed to be proud of their distinguished member. The Society of Exploration Geophysicists also is proud to have such an illustrious name on its membership rolls.

Father Macelwane, with a deep appreciation of the honor of acting as spokesman for the Society, I hand you this scroll certificate of Honorary Life Membership in the Society of Exploration Geophysicists as a humble token of recognition of your important contributions to our Society and to the great profession which it represents.

SIGMUND HAMMER

The Rev. J. B. Macelwane, S.J., right, received the Ninth Award of Honorary Life Membership from Sigmund Hammer during the 25th Annual Meeting.

TENTH AWARD OF HONORARY MEMBERSHIP

CITATION

It is doubtful that there is a geophysicist-geologist in the profession today who is as well known for the great breadth and variety of information at his command as the "walking encyclopedia" who is the third recipient of an honorary membership in the SEG to be granted at this time. How does a mind with such an unusual capacity for assembling information get to be that way?

Born at Carrolton, Kentucky, on the Ohio River, Paul Weaver's father and mother both were teachers. As a boy of nine his interest in science was first aroused when a Professor Miller, from Transylvania, a small college in Kentucky, came to collect fossils and happened to engage the boy

to drive a surrey, take care of the horses and help with the collections. There were Indian mounds and, under the Professor's guidance, he began to pick up Indian relics. Later, when his father became head of Brooklyn Boys' High School, this interest was continued and expanded by special classes and collecting trips for plants, insects and rocks, conducted by an inspiring woman of the children's Museum of the Brooklyn Institute. An early manifestation of his varied capabilities was a study of Greek with his father which led to his entering Columbia University with the highest entrance examination grade in Greek ever made there. Then, to show another facet of a diverse mind, while at Columbia, he won a mathematics prize for papers on partial differential equations and on the theory of probability.

His first job out of college was as a mathematician with the U. S. Coast and Geodetic Survey in Washington. After he had been there a year or so a small group of geologists of the Land Classification

Paul Weaver, right, received the Tenth Award of Honorary Life Membership from L. L. Nettleton during the 25th Annual Meeting.

Board, within the U. S. Geological Survey, decided that they needed a mathematician to carry out some rather complex calculations for the evaluation of coal lands, which required an analysis of thickness, quality and depth of the coal beds. Bill Heroy, of that group, who later became a geophysicist also, was commissioned to find a mathematician. He took his problem to William Bowie, whom many geophysicists know of for his work on Isostacy, and Paul's name was suggested. He was transferred to the Survey and thus began his first professional work in geology.

In another year, young Weaver became a good enough geologist to go to Trinidad and Venezuela with an oil company. This expedition ended in a year or so when he became so seriously ill with black water fever that he was about to be buried by the natives in his camp. But after being home a month or two he was back on his feet and went to Mexico for S. Pearson & Sons. His stay there was interrupted in 1914 by a revolution and Paul went to London with Whitehall Petroleum Corporation. This job was soon ended by the beginning of the first world war. He then joined British Intelligence and was sent to Japan to investigate mineral resources there and in Siberia. After that job was done he returned to Mexico where for some ten years he was superintendent and technical advisor

for the Mexican Eagle Oil Co. While there he pioneered in devising equipment to handle the gushers of the Tampico area and also started torsion balance surveys before they were used in the Gulf Coast. In 1926 he came to Houston with the Gulf Oil Company as geophysicist, later chief geophysicist and finally technical advisor to the Vice President until his retirement two years ago.

Paul had been known to geophysicists and geologists for his writings and also for his many lucid and fascinating talks and lectures. He has always had a fund of new ideas and suggestions in many fields. For instance, at the time of a visit to Europe in the early 1920's the only torsion balance was the Zuess instrument, manufactured in Hungary under the direction of Professor Eötvös himself This instrument was read visually through a small telescope. Paul thought it would be practical and much better if the instrument could be designed to be automatic in operation and with photographic recording. From this suggestion came the well known Bamberg torsion balance which shortly thereafter was put to work in Mexico.

After coming to Houston Weaver became interested in water supplies in the Houston area and in Texas in general. His ground water studies made him one of the first to realize that a priceless resource was being wasted and he began to preach water conservation. After retirement from the Gulf company he began teaching at Texas A & M and has continued his water conservation campaign. His public service has been recognized by his being named to the Governor's Water Committee of Texas, on the water committee of the South Texas Chamber of Commerce, and as a delegate to the United Nations Conference on Natural Resources. He has been honored both as a geophysicist and a geologist, having been President of the SEG in 1933 and of the AAPG in 1948.

Anyone who has known Paul Weaver or his friends has heard anecdotes about him. I will mention two that seem typical.

One time he was discussing the manner by which a young man read very rapidly by scanning two lines of type at a time. Paul said "that is pretty good but I take three going across and one coming back." Presumably this was for reading in English and may not apply to his reading in Spanish, Portuguese, French, German, Italian, Russian or Greek.

Another comes from an experience when he was on Sakhalin Island for British Intelligence during the first world war. It was desirable to make a hydrographic map of certain harbor entrances to see if they were deep enough to accommodate large ships but such mapping would have to be done secretly. How would you do that in mid winter with the harbor frozen over? Paul hired natives to fish for him through the ice at places he selected. He equipped them with fish lines marked with a code of knots of colored string to show their length. Then he went off with his plane table, took unnoticed shots to map his fishermen's locations, noted the positions of the colored knots on their lines and had depth points because, in winter there, the fish feed on the bottom. The fishermen never knew why they were moved around so much, regardless of whether they caught fish or not, but Paul had his map.

I am happy and honored to have been selected to present to Paul Weaver, scholar, scientist, geologist, pioneer geophysicist, public servant and highly regarded personal friend, this honorary membership in the Society of Exploration Geophysicists.

L. L. NETTLETON

ABSTRACTS OF PAPERS PRESENTED AT THE TWENTY-FIFTH ANNUAL MEETING

DENVER, COLORADO, OCTOBER 3–6, 1955

Specialized Mobile Equipment for Operations in Western Canada

F. B. WALLIS

The rugged, remote and inaccessible areas of Western Canada present obstacles to transportation which demand new and specialized vehicles for movement of seismic equipment. Although deep snow, heavy timber and rugged terrain offer certain handicaps to seismic operations, the primary obstacle to unrestricted movement in bush areas is the widespread occurrence of a ground moss called "muskeg." To overcome this barrier, several vehicles have been developed and are being used successfully

today in the search for oil. Three fundamental requirements of these machines are adequate power, exceptional traction, and a high flotation factor. The North King, Snowmobile, Scout, Bombardier and Sno-Car are examples. A short film demonstrates performance of the vehicles in some of the difficult operating conditions encountered in Western Canada.

Some Safety Aspects of Offshore Geophysical Operations from the Equipment Perspective

ARTHUR D. DARDEN

This paper outlines the existing authorities that govern marine inspection of vessels in service and under construction. It places the responsibility for the choice of the proper vessel including the features of safety and the qualified operations upon management.

Certain specific features of safety peculiar to geophysical service are discussed, including the proper grounding of electrical components in a wooden vessel. The stability considerations of a converted vessel and seaworthiness are discussed. In each case emphaiss is placed on the consequences of damage to property and bodily injury. The functions and ability of the naval architect are discussed where it is felt that his services based upon his qualifications and experience will contribute to a more efficient vessel and incorporate the safety features required by law and those which come from his experience.

Explosives for Marine Exploration

J. J. JAKOSKY AND J. J. JAKOSKY, JR.

This paper describes studies which have been underway since 1953 to determine the underwater characteristics of various types of explosives useful in off-shore exploration. Special instrumentation was developed for recording the pressure-time curves from underwater explosions.

The predominant characteristics of these curves have been related to seismic record quality and the destruction of fish and other marine life. The experimental studies have shown that non-lethal explosives are available which will give record quality and operating costs comparable to the conventional dynamites and which are much superior to the black powders.

Velocity Anisotropy in Stratified Media

L. F. UHRIG AND F. A. VAN MELLE

Velocity anisotropy has been reported by different authors (McCollum, Weatherby, White, and others) in Texas, Oklahoma, and Canada. The phenomenon includes anisotropy of the individual layers as well as an apparent anisotropy resulting from the time gain on oblique paths in a sequence of layers. The authors and their co-workers with Shell Oil Company made time measurements on oblique paths to seismometers in wells and studied late arrival refraction data in sedimentary basins in Texas. The anisotropy factor (ratio of horizontal to vertical compressional speed) was found to vary from 1.05 to 1.24. At the present time the amount of statistical data on velocity anisotropy is limited, and it is therefore suggested that additional observations be made. The interpretation of seismic data would certainly gain from a knowledge of the degree of anisotropy, especially in wide angle reflection work and in refraction surveys. This can be accomplished by adding offset shotpoints to routine well velocity surveys.

Some Hazards of Static Electricity to Users of Electric Blasting Caps

G. M. KINTZ and H. F. BROWNE

This presentation is not a "paper" in the true sense of the word; it is a demonstrated lecture. Explosives accidents at the shot point, involving premature ignition of explosives by static electricity from a thundercloud, are described and demonstrated. A real electric detonator is fired by throwing the short-circuited lead wires into the room atmosphere which has been charged with static from a small Van der Graaff machine. The effectiveness of static grids over shooting platforms on boats is also demonstrated. Methods of generating static with clothing and other materials, including dust,

are discussed and demonstrated. The effectiveness of static-resistant detonators is discussed, and recommendations regarding their use are given. Other types of explosives accidents are discussed, and recommendations for their elimination and the proper method of loading holes are given. No one subject to shell shock and no one seriously affected by explosions should attend this presentation.

The A.G.I. Serves You

E. A. ECKHARDT

At this anniversary meeting the growth experienced by our science and our society is naturally the No. 1 topic. It seems pertinent, however, to consider as well our position as one of many scientific professions and as an element of the national population. It is for service to the profession in this subject area that our society joined others in creating the American Geological Institute. The accomplishments of the Institute, its unrealized opportunities, and its problems will be discussed.

Review of Current Developments in Exploration Geophysics

MILTON B. DOBRIN and ROBERT G. VAN NOSTRAND

The most significant progress in exploration geophysics during the past year has been in the operational application of tools and techniques that were only in the development stage a short time ago. Magnetic tape recording and interval velocity logging are coming into extensive use in prospecting and contractors are offering both as commercial services.

Although current research in petroleum geophysics is concentrated more than ever before on the seismic technique, there have been important developments in the application of other geophysical methods to the search for solid minerals, particularly uranium. New logging techniques and airborne electromagnetic methods have been successfully applied for this purpose.

Interval velocity logs have given seismologists a better understanding of the process by which reflections originate from complexly layered formations. This understanding should lead to a more realistic interpretation of reflection data which may make it possible to map stratigraphic as well as structural features.

Other noteworthy developments in seismic prospecting during 1955 include new techniques for generating seismic energy, methods for more effective presentation of reflection data, and new approaches to the improvement of the signal-to-noise ratio on seismic records.

Some of the Habitats of Oil

G. M. KNEBEL

Detailed statistics have been prepared and studied for 236 or all of the major oil fields of the free world. They represent 217 billion barrels, which is 82.5% of the free world's expected ultimate. The study shows the bulk of our oil occurs:

1. On the stable side of basins.
2. In anticlines.
3. In sandstone and carbonate reservoirs.
4. From formations of Mesozoic age or younger.
5. From a depth range of 2,000 to 8,000 feet.

Most of the world's ultimate oil is 30° API gravity or above with mixed and asphaltic base oils predominating. The discovery of the "big" giants has been cyclic with 10-year intervals starting with the Lake Maracaibo discovery in 1917.

The Refraction Seismograph in the Alberta Foothills

GEORGE J. BLUNDUN

The primary purpose in the use of the refraction seismograph in the Alberta foothills is the mapping of the Madison limestone together with the detection and definition of faults. This paper will deal with the advantages and limitations of refraction, both in-line and broadside, initial program,

spread length, geophone separation, shot to spread separation, dynamite charges, system of survey and permissible tolerances, and other recommended field practices. Typical specimen seismograms and cross sections will be illustrated, as well as a gravity meter-refraction comparison of a typical limestone fault.

Alternative Modes of Seismogram Recording

F. S. KRAMER and R. A. PETERSON

A short discussion is presented on the relationship between the data traces on the seismogram and correlative geological features. Alternative modes of recording seismic data traces are then discussed, including various moving light spots, variable density, and coded flashing methods. Illustrative examples and comparisons are shown.

Recognition of the Effects of Diffraction in Exploration Seismology

JOHN BEMROSE

Reflection and diffraction of longitudinal waves are illustrated by slides and a slow motion film of wave motion in a shadow tank and a means of recognizing diffraction events on a seismogram by their migrational and other properties is demonstrated.

Symposium on Multiple Seismometers

MODERATOR—F. E. ROMBERG

F. A. VAN MELLE, F. F. REYNOLDS, R. L. PALMER, K. E. BURG

The various aspects of multiple-seismometer (and multiple-shot) exploration will be discussed by the participants in a ten-minute talk; each man will give his ideas as to the most important problems and pitfalls connected with such shooting. The economics of multiple shooting, the advantages to geologic understanding, the best methods of instrumentation, and the use of multiple shots and non-explosive energy, will be treated. There will be a question period for the participants themselves, after which the session will be open to questions from the floor.

Geophysical Case History Parentis Oil Field, France

R. VAJK and G. WALTON

In 1951, the French Government granted an exclusive exploration permit to the Esso R.E.P (a Standard Oil Company affiliate) over an area of 4,357,980 acres around Bordeaux in the northern part of the Aquitaine Basin. This area was investigated first by surface geology, then it was surveyed by the gravity meter. In checking the gravity anomalies by the reflection seismograph, a subsurface structure was found at Parentis in 1953, which was drilled in 1954, and was proved to be oil bearing. The Parentis oil field is the most important oil field, not only in France, but in all Europe outside the Iron Curtain.

Gravity map, seismograph map, seismic profiles, telluric map and geological contour maps, and cross sections of the Parentis structure are presented.

Majeau Lake, Alberta—A Discovery Resulting from a Restudy of Seismic Data

HUGO R. RENDEN

The discovery of the Majeau Lake oil and gas field resulted from critical re-examination of existing seismic records in an attempt to find the "Rundle pinchout" between two wells. Early development confirms the seismic interpretations but indicates the geology to be more complex than was originally thought.

Geophysical Comparisons at Dinuba Tulare County, California

MILTON C. BORN

A shallow unproductive structural anomaly near the town of Dinuba, California, was inferred from four different types of geophysical surveys and a subsequent core hole program. The similarity in contoured results of the applied methods is unusual in exploration history. Some idiosyncrasies in comparing geophysical methods are briefly discussed. Maps, derived from basic data of each survey, and sample seismic record reproductions are presented.

Good Hope Field, St. Charles Parish, Louisiana: A Geophysical Case History

G. A. BURTON

The Good Hope Field is located in the cypress swamps between the Mississippi River and Lake Pontchartrain near the northern limit of the south Louisiana salt dome province. Cumulative production to January 1, 1955, is 19,691,033 barrels of oil. Detailed reflection seismic surveys over a weak gravity anomaly disclosed a prominent structural uplift and suggested a deep-seated salt dome. Subsurface data from the field wells generally confirm the original seismic interpretation although no salt has been encountered by the drill to a depth of 11,259 feet.

Application of Velocity Logging to Exploration Problems

WARREN G. HICKS

Acoustic velocity logs have been made of wells located in widely separated areas with various lithologies. These logs have been useful in identifying reflections on seismograms, in determining vertical travel times, and in correlating strata from well to well.

Recent theoretical studies of elastic wave velocities for ordered packings of quartz spheres have led to the conclusion that the speed of sound through these packings will be appreciably lower when they are saturated with oil or gas than when saturated with water only. Continuous velocity logs of sand formations containing oil or gas have confirmed this theoretical conclusion. The depression of velocity is particularly marked in sands of high porosity where velocities measured in oil and gas sands have been 20 percent lower than velocities in salt water sands of the same porosity. This change in velocity may be attributed to the difference in compressibility between hydrocarbons and water.

Another factor affecting the acoustic velocity of a formation is its porosity. Velocity increases with decreasing porosity.

The velocity log thus provides supplementary information of value in locating oil and gas bearing reservoir beds and in differentiating between these and low porosity beds of similar lithology.

Resistivity of Sandstones as Related to the Geometry of their Interstitial Water

J. S. OSOBA, F. M. PERKINS, JR., and K. H. RIBE

It is extremely desirable in the interpretation of resistivity measurements made on porous media containing saline water and hydrocarbons to have at hand a better knowledge of the geometry of the conducting salt water.

One of the parameters used in describing this geometry is the tortuosity of the aqueous phase. A method was devised several years ago for the measurement of the tortuosity of completely brine-saturated sands by the measurement of transit time of ions migrating through the aqueous phase under a potential gradient. This method has been improved and extended to the investigation of the tortuosity of sands containing both brine and oil.

Results obtained to date on a group of sandstone samples containing water and oil indicate that there is a relation between the tortuosity of the aqueous phase, the brine content of the sand, the resistivity of the brine, and the resistivity of the gross sample. This, in turn, provides physical significance to the saturation exponent commonly used in well log interpretation. Results of this research may also have application to the multiphase flow of fluids through sandstones.

The Evaluation of Carbonate Reservoirs by Radiation Guard Logs

R. H. WINN

This paper presents a method of evaluating carbonate reservoirs from the radioactivity and focused resistivity surveys. The derivation of the method, its inherent limitations, and the relation of analytical technique to the petro-physical characteristics of rock matrices are discussed. Specific examples of successful application are illustrated.

The Practical Application of Digital Computers to Geophysical Problems

T. J. BEVAN and P. W. FULLERTON

The application of the electronic computer to the processing of geophysical data can be developed gradually, first by applying the computer to present computation techniques and later by improving the techniques themselves in order to make the mathematics more closely approach the physical situation. There are several rather elementary tests that can be applied in comparing desk calculator methods with electronic computing. The most important of these relate to the repetitive use of the basic data, the complexity of the calculations and the value of the accuracy and speed of the machine. The actual programming of the problem is a specialized field. The machine operator with an engineering background can set up the problem once it is clearly stated by the geophysicist. The computing service bureau can in many instances make operations economical because of its full-time utilization of the high speed of the machines. Applications to seismic and gravity data reductions which are in operation commercially are cited.

An Electric Gravity Analog Computer

W. W. GARVIN and J. W. NORTHROP

A number of methods exist to determine the gravitational effect of two dimensional mass distributions. These methods become cumbersome when extended to three-dimensional cases. For this reason, a special-purpose electric analog computer was constructed in 1950. The design of the computer was based on an analogy between the vertical component of gravity of a thin vertical prism and the current in an RC network. With the help of the computer it is possible to determine in a rapid and convenient manner the vertical component of gravity of arbitrary three-dimensional mass distributions. The gravity analog computer has been quite helpful in expediting detailed interpretation work particularly in salt dome problems. The present availability of general-purpose high-speed digital computers will probably make such special-purpose analog machines obsolete in the very near future.

Geophysical Type Magnetic Recorders

J. D. SKELTON

There are at present seven different commercially available magnetic tape recorders designed specifically for geophysical operations. These recorders differ in two fundamental ways: (1) the manner in which the tape is transported by the heads (drums, disc, reel, or endless belt), and (2) the recording method used (bias mixing, frequency modulation, or pulse width modulation). Various advantages and disadvantages of the different transport and modulation systems are discussed. The general form and special features of each commercial recorder are also described and illustrated. A drum-type transport and frequency modulation recording are most commonly used in the present-day recorders.

The operational and electrical specifications for each of the seven recorders are presented for comparison. Each model has a signal-to-noise ratio higher than 50 db and a frequency response that is flat from 10 to 300 cps. In all cases the maximum distortion is less than 2½%. Study of these commercial magnetic tape recorders indicates that each type should be amply satisfactory for use in geophysical field operations. The main difficulty at present is the lack of standardization of the various recorder specifications and methods for measuring the noise and electrical characteristics.

Magnetic Recording in Field Operations

HERBERT H. MOODY

Normal field use of the magnetic recording system by Continental provides an unfiltered magnetic record, a monitor record, and filtered records both with and without mixing. Periodic records are made with variations of equipment adjustments in efforts to improve routine procedure. Shifting of magnetic heads enables the application of individual trace corrections in rough topography or abrupt weathering changes, and many other improvements in seismic recording are within reach.

Recent Advances in Magnetic Recording and Playback Techniques

JOHN H. HIDY

The usefulness of seismic data stored and reproduced by magnetic recording methods can be greatly enhanced if the playback apparatus contains a large measure of flexibility.

Systems employing multi-record playback, with trace switching and selection, are briefly discussed. Examples of noise reduction and reflection identification are cited as typical improvements obtained by the use of new techniques made possible by this type of playback equipment.

Exploration History of the Block 12 Area Andrews County, Texas

J. H. DEMING and L. O. DAILEY, JR.

The authors review the general history of the Block 12 Area, Andrews County, Texas, from the first geologic interest in the area in 1920 to the present time. Successive torsion balance, gravimetric and seismic mapping are presented and discussed. Subsurface geologic mapping and a geologic cross-section based upon well control are also presented with a summary of the generalized stratigraphy.

The authors call attention to a seeming correlation between progressive changes in reflection character and truncation of geologic markers.

Summary of Selected Published Data on Seismic Wave Generation

RAYMOND A. PETERSON

A considerable volume of information, both experimental and theoretical, has been published which is pertinent to the use of explosives for seismic wave generation. An attempt is made to highlight the salient features of the explosion process by selected references, and to build a somewhat simplified picture of the complex physical phenomena involved.

Shooting in Sand

NORMAN RICKER

This paper describes field studies made in the Navajo Sandstone near Zion National Park in southwest Utah. Evidence is obtained that there is an abnormal absorption of elastic waves in the neighborhood of the shot, caused by a crushing of the sand grains by the explosion. This evidence is further supported by laboratory studies. To summarize the results of the studies, it may be stated that in the absence of sand crushing, the sandstone is quite transparent to seismic waves, but if crushing of the sand grains occurs there is intense absorption of the waves.

Seismic Attenuation in Pierre Shale

F. J. MCDONAL, R. L. MILLS, R. L. SENGBUSH, and J. E. WHITE

Near Limon, Colorado, where the Pierre shale is unusually uniform from depths of less than 100 feet to more than 1,000 feet, particle velocity waveforms were measured at distances up to 750 feet from explosive and other sources. Explosives gave a well-defined compressional pulse which was observed along vertical and horizontal travel paths. A weight dropped on the bottom of a borehole gave a horizontally-travelling shear wave with vertical particle motion. A horizontal force at the surface of the ground gave a vertically-travelling shear wave. In each case, signals from three-component

clusters of geophones rigidly clamped in boreholes were amplified by a calibrated, wide-band system and recorded oscillographically. The frequency content of each waveform was obtained by Fourier analysis, and attenuation as a function of frequency was computed from these spectra.

For vertically-travelling compressional waves, an average of six determinations over the frequency range of 50–500 cps gives $\alpha = 0.065\ f^{1.1}$ as the best fit. Fitting the data to $\alpha = 0.120\ f$ would imply only a small systematic error and should not be ruled out as a possibility. Less precise data for horizontal travel fitted either of the above equations acceptably.

For horizontally-travelling shear waves with vertical motion in the frequency range 20–125 cps, the results are adequately expressed by $\alpha = 105\ f$. For vertically-travelling shear waves in the frequency range 20–80 cps, $\alpha = 0.73\ f$.

In each case, the frequency f is in cycles per second and attenuation is in decibels per 1,000 feet of travel.

A High Frequency Multi-Channel Recording System for the Study of Blast

DAVID G. MURCRAY

The equipment described is in use at the Denver Research Institute and utilizes twelve cathode ray oscilloscope tubes to display the input signals. Recordings are made by photographing the two banks of oscilloscope tubes with 35mm. drum cameras. The result is a multi-channel recording system with a frequency response which is flat from D. C. to 80 K. C. Typical records obtained with this equipment are presented.

Some Observations on the Outgoing Seismic Signal

F. A. VAN MELLE

The elastic energy in the outgoing signal from a conventional seismic shot is computed from the recording by a subshot seismometer. In a good shooting area this proves to be less than one percent of the chemical energy liberated by the explosion.

The relations between the outgoing signal and the resulting reflection record are studied, and examples are given of differences in reflection times which result from changes in the outgoing signal. The terms "signal effect" and "signal correction" are suggested in this connection.

Measurements of Electrical Resistivity and Dielectric Constants on some Sandstone and Siltstone Cores

G. V. KELLER and P. H. LICASTRO

Measurements of dielectric constant and electrical resistivity at frequencies between 50 cycles per second and 30 megacycles per second were made on 27 cores from the Morrison formation of Late Jurassic age in the Uravan mineral belt of Colorado to obtain data to aid in the interpretation of geophysical surveys being made on the Colorado plateaus in the search for uranium and vanadium ores. A wide range of values was found for both parameters. Electrical resistivity varied from 10^2 to 10^{12} ohm-centimeters, and dielectric constant varied from 4.0 to more than 10^6. The water content of the cores seems to be the controlling factor, the high resistivities being associated with low water content, and the high dielectric constants with high water content.

Theory and Application of a Dual Frequency Airborne Electromagnetic System

D. G. MACKAY

The problems involved in inductive electromagnetic surveys from aircraft are reviewed and the relative merits of phase and amplitude measurement discussed. Phase measurement equipment operating on two independent frequencies is described, and the installation of the equipment in a PBY5a aircraft illustrated.

A number of examples, taken from actual surveys, are given showing the method of presentation of the data, the interpretation placed upon various anomalies, and also something of the results achieved.

In conclusion, an opinion is expressed on the proper application of this type of airborne survey to modern mining exploration.

Regional Aeromagnetic Interpretation in the Precambrian Shield

L. W. MORLEY

Mathematical processing of aeromagnetic contour data in regional studies of the Pre-Cambrian is more laborious and less necessary than in regions of mixed sedimentary and intrusive rocks. Furthermore, in the total job of interpretation, the uncorrected contour data is as perfection in comparison to the final step of interpretation, that is the final jump from data to geology. This situation exists because of the profound lack of knowledge of factors controlling the deposition of magnetite in igneous and metamorphic rocks. Some examples of regional interpretations in the Pre-Cambrian are given.

The Graphical Calculation of Total-Intensity Anomalies of Three-Dimensional Bodies

ROLAND G. HENDERSON

Calculation of the total-intensity anomaly of a three-dimensional body of arbitrary shape is greatly facilitated by the orthographic projection of a topographic map of the body on a plane normal to the inducing field. The graphical integration is then effected by means of a modified Gassmann integration process. Applications to theoretical and laboratory models establish the relative accuracy of the method. Examples are given of applications to observed anomalies over geologic structures.

Terrain Anomalies in Magnetic Surveys

P. A. RODGERS and J. C. HOLLISTER

The terrain effect on magnetic anomalies measured in mountainous areas where the intensity of magnetization of the rocks is of the order of .001 may sometimes be large enough to seriously distort significant anomalies and should be taken into account. Examples are given of magnetic profiles corrected and uncorrected for the terrain effect. The usual assumption is made that the magnetization is in the direction of the earth's field. A table has been computed for magnetic inclination 68° to be used with a zone chart similar to the kind used for terrain corrections in gravity surveys.

Regional Gravity Survey in Salt Lake and Utah Counties, Utah

KENNETH L. COOK and JOSEPH W. BERG, JR.

During June to August, 1954, U. S. Geological Survey made a regional gravity survey in Salt Lake and Utah Counties, Utah. Gravity measurements were made at 1,100 stations in an area of about 2,100 square miles, and the results have been compiled as a Bouguer gravity anomaly map.

Past tectonic activity in the region has been great, and the regional gravity patterns reflect the present contrasts in the crust that are the product of several orogenies. A gravity high occurs over the northern Utah highland in the Antelope Island area. The gravity data give no evidence that the Uintah arch extends west of the Wasatch front. Steep gravity gradients corresponding with Basin and Range faults occur along (1) parts of the Wasatch fault zone; (2) a continuous fault zone 60 miles in length along the west margin of the Oquirrh, Boulter, and East Tintic Mountains; and (3) the Utah Lake fault zone east of Lake Mountain and West Mountain. A gravity high corresponds to the great fault block comprising the Oquirrh, Boulter, and the northern part of the East Tintic Mountains. The gravity data indicate that in the valley areas between this fault block and the Wasatch fault block, a great intermont trough more than 100 miles long comprises a great belt of graben and smaller fault blocks of varied dislocations. Several large fragments lying immediately west of the Wasatch block have apparently dropped deeper than the other fragments as if slipping into a great crevasse.

A Theoretical Map of the Basement in Indiana Derived from Aeromagnetic Data

ISIDORE ZEITZ and JOHN R. HENDERSON

An aeromagnetic map of Indiana has been compiled on a scale of 1:500,000 from published U. S. Geological Survey aeromagnetic county maps. A map of the Precambrian basement rocks has been

constructed from depth determinations of more than 80 isolated aeromagnetic anomalies. The magnetic trends on the basement rocks are in general similar to the trends of the structure contour map of the top of the Trenton (Ordovician) limestone. There is also excellent agreement between the map and the 6 depths to basement rocks found by well drilling.

The contours on the basement rocks indicate the possible existence of a major northwest-striking ridge approximately 50 miles wide that does not appear on the structure contour map on the top of the Trenton limestone. The existence of the ridge is partially confirmed by large gravity and magnetic anomalies at almost the same place.

Geology of the Blind River Uranium Area Ontario, Canada

D. S. ROBERTSON

Conglomeratic sediments of the Blind River area carry uranium in the minerals Brannerite, Pitchblende, Uraninite, and Thucolite in order of probable importance. Proven ore tonnages are approximately 50 million tons. Most of this has already been purchased by the government under contracts amounting to approximately 450 million dollars ($450,000,000). Estimated tonnages are on the order of 300 million tons.

Primary structures appear to control the ore and preliminary investigation suggests that the richer bodies are associated with hollows in the basement and with relatively steep basement dips.

Studies of structure and stratigraphy indicate that the present basinal structure is a deformed part of the north limb of a larger basin or geosyncline that occupied a large area stretching at least 200 miles in an east-west direction. The older sediment of this large basin is all uranium bearing. The present basinal character began to appear in late Mississagi time and was completely formed by Gowganda time.

Intense faulting of both thrust and high angle character has been noted on the limbs of the basin. In the vicinity of Pronto Mine, granite gneiss of the basement is thrust over ore bearing conglomerate for at least thousands of feet.

The ore appears to be of sedimentary origin.

Regional Geophysical Studies in the Uravan District, Colorado

P. EDWARD BYERLY and H. R. JOESTING

Regional gravity and aeromagnetic surveys have been conducted in the Uravan district of southwest Colorado by the U. S. Geological Survey as part of a study of major geologic structure in the Colorado Plateau. The Uravan district includes approximately the area between latitude 38°00′ and 38°45′, bounded on the west by the meridian 109°00′ and on the east by the Uncompahgre Plateau and the meridian 108°22′ 30″.

Elevations of gravity stations were determined from bench marks and by altimetry. The major gravity variations are due to changes in composition of the basement rocks and to variations in thickness of salines in the Paradox member of the Hermosa formation. Large negative anomalies are associated with the Paradox Valley and Gypsum Valley salt anticlines.

The major magnetic anomalies are related to changes of composition in the basement and to faults involving large displacements of basement rocks. The Uncompahgre uplift shows large anomalies. Smaller anomalies along Disappointment syncline suggest a downwarp resulting in a basement trough of comparatively great depth between Disappointment syncline and the Uncompahgre uplift.

Geophysical-Geochemical Prospecting for Uranium

M. E. DENSON

Physical and chemical properties of sedimentary rocks associated with uranium deposits have variations which indicate applicability of geophysical and geochemical exploration methods. Some of the variations in the properties can be attributed to geologic factors and phenomena connected with deposition of ore. Correlations between chemical and physical properties are used as a guide for sequencing of field techniques.

Geophysical field data are supplemented by geochemical data on trace quantities of uranium, thorium and potassium. These data are augmented by other chemical information on soils, waters, and gases to serve as a guide for evaluation of prospective areas. Examples of such field data, including shallow seismic reflection, surface and in-hole resistivity, surface radiometric, and geochemical, from areas in South Dakota, Wyoming and Colorado are presented to show the types of detectable physical and chemical variations found to be significant.

Exploring for Ancient Channels with the Refraction Seismograph

L. C. PAKISER and R. A. BLACK

In the Monument Valley of Arizona and Utah, uranium ore has been found in ancient channel deposits, primarily in the Shinarump conglomerate of Late Triassic Age. The seismic velocity in the Shinarump is substantially less than that in the Moenkopi formation of Early and Middle (?) Triassic age, which unconformably underlies the Shinarump. Therefore, the ancient channels can be located by using the refraction seismograph. Because the Moenkopi erosion surface in channel areas is curved, a delay time method of analysis is used to determine the position in depth of the Shinarump-Moenkopi contact. The problem of velocity variations within the Shinarump can be overcome by bold interpretation supported by drill-hole and velocity control.

Aerial Radiation Surveys for Uranium Prospecting

F. J. DAVIS

The U. S. Geological Survey and the Atomic Energy Commission in a joint project have developed and operated equipment (from a twin engine DC-3 type aircraft) for making radiation surveys of the ground. The equipment uses six NaI scintillation crystals, each 4 inches in diameter by 2 inches thick, which feed pulses through amplifiers to a recording rate meter. Auxiliary equipment includes strip film camera and radio altimeter; the radio altimeter coupled to the recording rate meter compensates the radiation record for variations in height above ground.

At 500 feet above ground, the normal background count is of the order of 500 cts/sec; of this 200 cts/sec are due to soft cosmic rays and 300 cts/sec to gamma radiation from the ground. As a consequence of the build-up of scattered radiation, the variation of the gamma-ray intensity with height from large area sources can be expressed as $I = e^{-ub}$ where u is the absorption coefficient determined by the energy of the source radiation.

Analysis of Air-Scattered Gamma Radiation from Thick Uranium Sources

A. Y. SAKAKURA

To obtain quantitative results from airborne radioactivity surveying, a knowledge of the intensity pattern of gamma radiation from uranium sources of various sizes and grades is necessary. Moreover, the observed data recorded on a counting rate meter such as a peak intensity (counts per second), as well as the area under the curve (total counts) and the shape of the curve must be correlated with the principal characteristics of natural sources—the grade, in terms of equivalent uranium oxide content, and the configuration, in terms of equivalent uranium oxide content, and the configuration, in terms of the surface dimensions. As configurations of natural sources are ordinarily highly complex and thus difficult to analyze, measurements have been made on an elementary artificial source, essentially a point in extent of infinite thickness. Idealized sources were then synthesized by the superposition of the elementary source, guided by the known theoretical absorption and scattering of gamma rays. The method of interpretation developed on the basis of these calculations has proved generally adequate for interpreting airborne radioactivity survey data.

The Application of Semi-Quantitative Methods to Airborne Radioactivity Surveying

R. M. MOXHAM

Results of experimental airborne surveys over an artificial carnotite ore body and a natural semi-infinite source have been used to relate the behavior of an airborne scintillation detector to the area,

grade, and geometric conditions of four basic source configurations: point, finite, slab, and infinite plane.

The method of analysis of flight data obtained by systematic surveys, as devised by Sakakura, has been applied to several selected surveys. Results indicate that for infinite sources the grade can be determined to within a few thousandths of one percent equivalent uranium oxide and the limits of the anomaly fixed within a few hundred feet. Determination of the grade x area product of point sources may be in error by as much as a factor of two and determinations of point source position by several hundred feet. Errors relating to analyses of slab and finite sources are generally of the same order of magnitude, with errors increasing inversely with the size of the source. The analytical methods utilized were devised principally for the technique and equipment employed by the Geological Survey but the analytical procedure is generally applicable to measurements by any scintillation detector of comparable energy response.

TRANS-PECOS STUDENT SECTION HEARS SENATOR BERMUDEZ

On Tuesday, November 8, Senator Antonio J. Bermudez, Director General of Petroleos Mexicanos (PEMEX), delivered an address before the membership of the Trans Pecos Student Section, Society of Exploration Geophysicists. The chief of Mexico's oil industry spoke before a near capacity crowd in Magoffin Auditorium, on the college campus in El Paso.

The Senator's arrival, the night before in Cd. Juarez, marked his first visit to his native city in nine years. He was greeted at International Airport by thousands of school children and friends. As he stepped from his personal plane, El Petrolero, he was presented with hundreds of gifts and bou-

Group photo in Magoffin Auditorium, Texas Western College, prior to Senator Bermudez' address. (Left to Right) Dr. Dysart Holcomb, President of Texas Western; Senator Antonio J. Bermudez, Director-General of Petroleos Mexicanos (PEMEX); Cecil H. Green, Chairman of Geophysical Service Incorporated; John T. Sample, Jr., Council Chairman of the Trans Pecos Student Section, SEG; and Barry B. Shaw, Co-chairman of the program committee.

quets of flowers. In a brief speech at the airport, he gave the Student Section's invitation to talk at Texas Western as the reason for his return to the border.

From the stage of Magoffin Auditorium, Bermudez said, "Searching for oil is a fascinating business, but today we must conduct that business on good, sound geophysical and geological information.

Further exploration is going to depend upon new talent which must come from the ranks of such colleges as Texas Western."

Senator Bermudez told of how his country is somewhat handicapped because of the lack of facilities to drill for oil. He added, however, that Mexico now has eight refineries throughout the country capable of handling a total of 330,000 barrels a day.

He said that because of a shortage of facilities, Mexico is forced to "import many refined products."

"Importation is bad for the economy of my country . . . it is our own worst enemy," he said, adding that this included Mr. R. G. McIntyre, President of the Standard Oil Company of Texas, who was present during his address (PEMEX buys 5,000 Bbls. of refined gasoline from Standard of Texas each month).

The senator was introduced by Cecil H. Green, Chairman of Geophysical Service Incorporated, Dallas, Texas. Mr. Green, longtime friend of Bermudez, said "the international petroleum industry is extremely proud of Senator Bermudez."

Others on the program included Dr. Dysart Holcomb, President of Texas Western College; Barry B. Shaw, co-chairman of the program committee; and John T. Sample, Jr., council chairman of the Student Section, who read a special message from Governor Allan Shivers welcoming Bermudez to Texas. Governor John F. Simms of New Mexico, and Governor McFarland of Arizona, both sent special messages, expressing regret that they could not be present.

That evening, the Student Section was host at a dinner in the Senator's honor at the El Paso Country Club. The Standard Oil Company of Texas co-sponsored the dinner, which was attended by one-hundred and fifty local and out-of-town guests. Among those who attended were: Cecil H. Green; Dr. General Jesus Lozoya Solis, Governor of the State of Chihuahua, Chihuahua City, Mexico; El Paso Mayor Tom E. Rogers; Major General Paul W. Rutledge, Commanding General, Fort Bliss, Texas; Major General John Reynolds, Commander, Biggs Air Force Base; General Terry Allen, U. S. Army (Retired); Hugh F. Steen, vice president of El Paso Natural Gas; C. C. Tucker, president of Lea County Gas Co.; Boyd E. Ryan, president, Proveedora Rio Bravo, S. A.; E. C. Donohue, president, Sun-Tex Petroleum Co.; Spencer Darbyshire, president of Darbyshire Steel Corporation, Honorable R. E. Thomason, U. S. District Judge; and Sr. Rene Mascarenas, chairman of the board of Water-Fill Fraser Distillery, S. A., and the Banco de Juarez.

Senator Bermudez' visit to El Paso was sponsored by Geophysical Service Incorporated, as a part of the Trans Pecos Student Section's Distinguished Lecture Series in the Earth Sciences for 1955–1956.

ABSTRACTS OF PAPERS PRESENTED AT THE NINTH ANNUAL MIDWESTERN MEETING, HOTEL TEXAS, FORT WORTH, MARCH 8 AND 9, 1956

Antarctic Research in Connection with the International Geophysical Year

HARRY WEXLER, Director of Meteorological Research, U. S. Weather Bureau and Chief Scientist, U. S. National Committee, International Geophysical Year Antarctic Program 1955–1959

During 1957–58 a dozen nations will establish thirty-five geophysical stations in Antarctica. Thus, this continent, whose area is larger than that of the United States and Mexico combined, will be the subject of concentrated, coordinated geophysical exploration, to a degree not dreamed possible a few years ago. For the first time geophysical stations will be established away from the coasts, deep in the interior of the continent. Scientists from the various nations will cooperate in exploring the temperatures, winds, and electrical properties of an atmosphere cut off from sunlight for many months. The

thickness of the ice will be surveyed and examined for indications of increase or decrease of its volume over the years, to see if Antarctic climate is changing. The Aurora Australis will be photographed and compared with its Northern Hemisphere counterpart, the Aurora Borealis. Intensive measurements will be made of geomagnetism, cosmic rays, airglow, and the ionosphere in an attempt to throw light on physics of the high atmosphere.

Seismograph Correlation Between Permian Reef Line and Basin Type Section, Hockley County, Texas

JOHN DALY, Consultant in Geophysics and Geology, Midland, Texas

The purpose of this paper is to demonstrate that the seismograph is a useful tool in solving stratigraphic problems in the Permian Basin area. The correlation of the massive carbonate deposits of the barrier reef line with the bedded clastics and carbonates of the basins is particularly difficult. These sedimentary changes are often marked by anomalous reflections arising from the detritus-carbonate interface on the basinward, steeply dipping scarp of a reef line. In parts of Hockley County, Texas the reef dips are good and can be carried continuously from the basin over the reef line and into the back reef or lagunal areas. The massive dolomite of the reef section which occurs about 300 feet below the top of the Tubb zone is correlated with the base of the Dean sand.

Geological Outlook

A. I. LEVORSEN, Independent Geologist, Tulsa, Oklahoma

Geologists and geophysicists have the same outlook, and whoever practices one must of necessity practice the other. They are not separable. Our joint outlook, then, is first, for a continuing acceleration in petroleum demand which makes an increasing rate of discovery a basic essential to the petroleum industry. The answer to the question "Is it there to be discovered?" is personal, but there seems to be adequate unexplored geology to justify the conclusion that petroleum in amounts necessary to meet the demand awaits discovery. The final question, "Can it be discovered?" depends on two factors that have become typically American. These are, 1) the opportunity to continue multiple effort as a way of exploration, and 2) the opportunity to continue an equilibrium of opportunity in the management of exploration. With these two, the petroleum can be discovered, but without them the chances are that the petroleum will remain in the ground, undiscovered and useless.

Geophysical Outlook

HOLLAND C. MCCARVER, Seaboard Oil Company, Dallas, Texas

What is the outlook of geophysics? This very timely and thought-provoking question is of concern to all petroleum exploration people. If geophysics is to continue in its dominant role of oil-finder, definite and productive steps must be taken in the field of technical advances, economics, personnel and application. Regardless of impressive superficial advances, the geophysical tool must steadily contribute to the discovery of new oil reserves or it will not be used.

The Unit Approach

JOHN H. FOLKS, The Carter Oil Co., Oklahoma City, Oklahoma

Rising land costs coupled with limited available seismic coverage in basins presently covered by diverse checkerboard protective leasehold ownerships dictate an improvement in methods of evaluation heretofore employed. Drilling of prospects by accepting the conventional dry hole or acreage contributions with or without overrides no longer constitutes an equitable arrangement. The objections to creating Mutual Areas of Interest and subjection of leaseholds to Joint Operating Agreements must be overcome. One of the outstanding objections has been the amount of effort and loss of time that is inherent in negotiating an operating agreement which is acceptable to the unit partners. This feature will be greatly overcome by a Model Form Operating Agreement which will be available to industry in 1956.

Phase Linearization of a Complete Seismic System and Some Field Results

G. C. Phillips, L. M. Mott-Smith and W. J. Gundlach, General Geophysical Company, Houston, Texas

Although it is well known that the phase characteristic of the complete detecting system should be linear if the output is to reproduce faithfully the input, little has been reported in investigating applications to the seismic technique. An analogue computer, of the electrolytic tank type, was used to design a compensator for a conventional *complete* seismic system. The resulting overall phase characteristic was linear between 12 and 120 cycles/sec. The method of designing the phase compensator will be discussed and some typical compensated and uncompensated field records will be compared.

Alternative Modes of Seismogram Recording

Frederick Stanley Kramer and Raymond A. Peterson, United Geophysical Corp., Pasadena, California

A short discussion is presented on the relationship between the data traces on the seismogram and correlative geological features. Alternative modes of recording seismic data traces are then discussed, including various moving light spots, variable density, and coded flashing methods. Illustrative examples and comparisons are shown.

The Moveout Filter

Carl H. Savit, John T. Brustad and Joseph Sider, Western Geophysical Co. of America, Los Angeles, California

The response of a seismometer array or "pattern" is a function of the wavelength (also of the moveout or phase velocity) of incident energy. Patterns are thus "moveout filters." The present paper develops the general theory of arrays and gives an explicit solution for the design of an array having a predetermined moveout response.

It is further shown that the antenna theory approach to pattern design in inadequate in the seismic case by reason of the non-uniqueness of the velocity of incident energy.

An example of a pattern designed to meet specific requirements is exhibited. The case presented effects a calculated improvement of at least four to one in signal-to-noise ratio over conventional patterns. The output of the designed system for a horizontally traveling, transient pulse input is shown to be greatly reduced in peak amplitude.

Approximately two years of experimentation and field use of newly designed arrays in several areas indicate that the inconvenience and high cost of present day pattern work can be reduced while at the same time results are substantially improved.

Scientific Explorations by Means of Earth Satellites

Fred L. Whipple, Smithsonian Astrophysical Observatory and Harvard College Observatory, Cambridge, Massachusetts

The United States Earth Satellite Program presents unparalleled opportunities for certain geophysical measurements to be made both by sending equipment in the earth satellite and by observation of the motion of the satellite from the surface of the earth. The measurements of ultraviolet and X-ray solar radiation which affects the ionosphere and upper atmosphere can be made directly from the satellite and telemetered to the earth. Further observations include cosmic rays and soft corpuscular radiation from the sun as well as meteoric impact and other local phenomena on the satellite itself. Observations from the ground provide measurement of the density of the high atmosphere several hundred miles above the earth's surface, extremely precise interlacing of geodetic systems from one continent to another, the shape of the earth to extreme precision and considerable information concerning the distribution of mass in the earth, isostasy and other geophysical parameters. The wealth of material that can be obtained from an exceedingly simple, small and lightweight satellite indicates the enormous potentialities of future larger satellites with permanent power supplies.

"Provinces for Future Exploration"—West Texas and New Mexico

WILLIAM A. WALDSCHMIDT, Consulting Geologist, Midland, Texas

The major geological provinces of West Texas and southeastern New Mexico, and subdivisions thereof, are reviewed briefly in an attempt to select in a general way some of the areas that might be considered to be oil provinces for future exploration. Of the established geological provinces, the Delaware and Val Verde basins are considered worthy of additional exploration. Some of the smaller areas, or subdivisions of the established geological provinces, also believed good for further exploration, include the east and southwest flanks of the Delaware Basin, the west edge of the Eastern Shelf, the area along the west side of the Midland Basin, and the large atoll-like trend at the northern end of the Midland Basin. The paper is concluded with suggestions that might be helpful in planning exploration in these areas.

Subsurface Provinces, and Future Exploration in Oklahoma, Kansas, and North Texas

CARL A. MOORE, Chairman, School of Geological Engineering, University of Oklahoma, Norman, Oklahoma

A great number of petroleum exploration techniques are being utilized in the search for oil in Oklahoma, Kansas, and North Texas. Current emphasis is being placed on locating a favorable geological area, or province, and then adapting the proper exploration tools to the problem of finding oil in that favorable area.

In this area there are a number of subsurfaec provinces, each of which is now being actively explored for oil. These provinces include the broad uplifts on which many major fields have been found, and the sedimentary basins and embayments in which present exploration is being conducted with sporadic success. An attempt is made here to evaluate this current exploration activity.

Areas of Promise for Future Exploration—Mississippi and Alabama

WILBUR H. KNIGHT, Union Producing Company, Jackson, Mississippi

The most promising area for future exploration is in the Lower Cretaceous rocks of Southern Mississippi and adjacent Southwestern Alabama. It is believed that additional exploration in this area will result in the discovery of new substantial oil and gas reserves. To date, discoveries in this province, with one exception, have been the result of subsurface prospecting; however, any long range exploration program will have to depend, for the most part, on seismic work inasmuch as most all the better subsurface prospects will soon be tested.

The Black Warrior Basin of Northeastern Mississippi and Northwestern Alabama remains an area of promise. Development to date in this Paleozoic area has been disappointing; however, all the components of a productive sedimentary basin are present and it is believed that if wildcatting is substantially increased, the discovery of new important reserves will inevitably result.

Evolution of Seismic Instruments

JOHN P. WOODS, The Atlantic Refining Co., Dallas, Texas

Seismic prospecting is thirty years old. In this time, seismic instruments have changed greatly. The problems of prospecting are now more difficult. To meet the increased difficulty, seismic instruments have been changed so that much more data are taken. The approach has been statistical; the bad data are cancelled by various averaging processes. In the past there have been several near revolutions in the seismic method. Today it appears that great changes in instruments and methods may come from the introduction of magnetic recording, computing machines, correlation machines, and the generation of seismic waves by weight dropping. At present, it is hard to evaluate these possibilities.

Getting the Most Out of Present Seismic Instruments

J. E. HAWKINS, Seismograph Service Corp., Tulsa, Oklahoma

Much of the present seismic work is being carried out in areas where results are difficult to ob-

tain. The paper outlines the requirements for seismic instruments for these operations. The particular characteristics desired for specific problems are illustrated, and the instrument factors that affect these characteristics are outlined. Examples of the effects of instrument adjustment are shown. Means of arriving at optimum results with present equipment under diversified field conditions in different areas are illustrated by specific cases.

Some Peripheral Digital Computer Equipment for Seismic Data Processing

D. W. PATTERSON, Benson-Lehner Corporation, Los Angeles, California

A discussion on types of input-output equipment, the digital computer bottleneck, is given. The accomplishment of high-speed computing has greatly reduced the time lost and inaccuracies in processing raw data. However, the computer has created a greater need for better input-output processing. Some examples of these peripheral equipment types, including the most recent developments, are given.

Research Horizons

DAYTON H. CLEWELL, Magnolia Petroleum Company, Dallas, Texas, and Chairman of the SEG Research Committee

Prediction of future research can be the most uncertain of all predictions. However, to the extent that necessity is often the mother of invention, we can expect the rising costs of oil exploration to greatly influence current projects in exploration research. Research in both geology and geophysics will be aimed at the stratigraphic trap. A great amount of geological research work will be concerned with the details of the origin of oil and the origin of reservoirs. This kind of information is needed to stimulate new thinking about where to look for new oil. We can expect to secure much more subsurface information from drilled wells than we have ever done in the past. It also appears that we are on the verge of really substantial advances in our ability to do a better job of interpreting geophysical data.

The Geologic Causes of Gravity Anomalies

ROBERT J. WATSON, The Carter Oil Co., Tulsa, Oklahoma

The appearance on gravity maps of various kinds of anomalies to be expected in a basin area is demonstrated by means of synthetic examples. Conditions of density contrast and structural relief necessary to produce detectable anomalies are shown. The possibilities of these favorable conditions being present in the Mid-Continent area are briefly considered.

Application of Gravity Anomaly Simulator

LAWRENCE STRICKLAND and FREDERIC ROMBERG, Geophysical Service Inc., Houston, Texas

There is a need in the industry for an easy way to determine the gravity anomaly of the irregular shaped bodies. The gravity anomaly simulator fills this need. The simulator is based on the fact that the illumination at a point above a surface which obeys Lambert's law can be determined by the equation:

$$L = k \int \frac{\cos \theta}{r^2} \cdot dxdy$$

Similarly, the anomaly due to a body can be approximated by:

$$g_z = (\Delta P)(\Delta z) z_0 \int \frac{1}{r^3} \cdot dxdy$$

These equations are equal within a multiplicative constant. The simulator consists of a source of light, a photocell, the amplifier, means of displaying the current through the cell, and means for positioning the photocell. If proper precautions are taken, results can be obtained to within 5 percent of the maximum value of the anomaly. Irregular volume distributions can be approximated by constructing them for several elemental distributions.

Practical Applications of Magnetic Methods in Oil Finding

JAMES AFFLECK, Gulf Research & Development Co., Pittsburgh, Pennsylvania

The utility of the magnetic method in an exploration program is discussed.

The sources of magnetic anomalies and basement characteristics are described. The paper includes typical profiles over basin and uplift zones and samples of magnetic data and derivatives over known structures.

Interpretation of the Results of Magnetic and Gravimetric Surveys with the Aid of Modern Electronic Computing Equipment

E. G. KOGBETLIANTZ, IBM & The New School for Social Research, New York

The fantastic speed with which modern electronic computers perform the fundamental arithmetic operations opens unlimited possibilities for improving the scope and accuracy of technological computations. This paper discusses the use of electronic data processing machines for the computation of the regional anomaly, derivative maps and the continuation downward to various depths from a given observed anomaly map.

Magnetic Tape Can Find More Oil

PHIL P. GABY, Delta Exploration Co., Jackson, Mississippi

Advantages to be obtained with magnetic tape may be broadly divided into:

1. Storage of data with intent to derive advantage from future development of any techniques.
2. Facilitate present research.
3. Obtain sufficient present advantage and improvement to allow finding oil NOW that probably would not be found otherwise.

A clear policy decision is required between one and three as these are mutually exclusive to a large degree. This paper deals with present use of tape indicating several general types of cases where substantial improvement is now available through, and only through, magnetic recording. Sample record-cross-sections will be available for inspection.

Report on Continuous Velocity Logging

HOMER W. LAWRENCE

Several types of velocity logging tools are presently in use, some on an experimental basis and others commercially. Those types on which information has been released are briefly described.

Velocity logs have been run in over 750 wells, about half by oil companies using their own instruments and the other half by commercial contractors. Geographical distribution of the wells logged is wide and includes Canada, Venezuela, France and England as well as the United States.

Applications of velocity logs, other than as a velocity tool, are increasing with the corresponding increase in the number of wells logged. The correlation potential of the logs is immediately apparent. Recent experimental work and papers have pointed out velocity-porosity relationships and possibilities of determining fluid content.

Difficulties in Seismic Prospecting Resulting from Bubbles in Fluids

J. O. PARR, JR., Consulting Geophysicist, San Antonio, Texas

Small percentages of gaseous bubbles present in fluids or semifluids can cause serious difficulties in seismic prospecting. Shot hole fatigue, reversals of polarity and large times for short intervals in deep well surveys, reflections coming into side of geophone line from surface anomalies—particularly in water, and variations in the seismic velocity through water in the Gulf of Mexico can be caused by bubbles. Both records and theoretical data are shown to substantiate this hypothesis.

MEMBERSHIP APPLICATIONS RECEIVED

Applications for Active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the name of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the President within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

Peter B. Bike (Richard M. Bradley, William H. Courtier, Vincent Miller)
Raymond R. Bristow (James H. Dunaway, D. H. Gardner, W. H. Berleth)
Francis X. Cannaday (H. E. Stommel, F. W. Hinrichs, Ralph C. Holmer)
R. C. Cashin (E. M. Wolters, P. M. McNally, W. H. Courtier)
Ugo Collendan (Carl H. Savit, Thomas P. Maroney, M. A. Boccalery)
Joseph C. Colvin (Keith R. Beeman, E. J. Shimek, Paul Farren)
John H. Crump (P. E. Mackey, F. P. Kokesh, R. R. Rosenkrans)
G. W. Fawcett (R. J. Copeland, R. B. Ross, Wm. Blair, H. J. McGrew)
Homer L. Fitch (George Augustat, R. E. Crandall, J. W. Anderson)
James E. Galloway (Dosh T. McCreary, Turner L. Kunkel, Otis B. Hocker)
D. J. Gear (G. Andrew, Robert F. Dundon, K. Davies)
Fraser S. Grant (R. F. Weichert, F. H. Cady, G. G. Walton, R. J. Watson)
Hajime Hayashi (D. D. Mize, H. R. Frank, H. A. Sears)
Frank M. Johnson, Jr. (E. G. Dobrick, H. C. Bemis, S. C. Stoneham)
Shoichi Kunori (Syunitiro Omote, Kuniyuki Katayose, Seibe Onodera, Kumiji Iida)
Robert B. McCaskill (S. W. Schoellhorn, Ben F. Rummerfield, J. E. Hawkins, R. P. Green)
Walter A. McNeil (R. Maxey Pinson, Elwin Peacock, A. A. Hunzicker)
Hari Narain (C. E. Marshall, W. Bonini, L. L. Nettleton, K. E. Bullen)
C. W. Penny (Ronald E. Wright, Chester Sappington, Kenneth R. Wells, T. O. Hall)
Jack W. Putnam (Delbert F. Smith, W. H. Roane, J. Kenneth McDonald)
K. H. Sawyer (Herbert Dawson, R. F. Weichert, G. M. Knebel)
R. D. Sehested (E. H. Weltsch, Jack L. Friendly, H. C. Schaffer)
J. D. Skelton (R. D. Lynn, J. B. Bayhi, S. E. Giulio)
H. J. Thiele (John Ohman, L. Mintrop, Richard A. Geyer, B. Baars)
Pascal Vetterlein (Hans Wilhelm Maass, Hans von Helms)
John H. Wright, Jr. (W. J. Pfeffer, H. L. Copeland, M. C. Baker, Wm. E. Strain)

APPLICATIONS FOR TRANSFER FROM ASSOCIATE TO ACTIVE MEMBERSHIP

George E. Anderson, Jr. (D. W. Ratliff, P. H. Garrison, J. R. Foster)
L. R. Baxendale (H. E. Shell, E. J. Northwood, J. Murphy, T. E. Dennis)
Robert J. Bean (K. S. Cohick, Frank Goldstone, W. Hafner)
Dilliard L. Brooks (John L. Care, C. H. Wallace, H. M. Cooper)
Leelvy Compton (R. H. Burton, Louis H. Michaelson, A. D. Mehringer)
Edward G. Coughlin (L. F. Melchior, J. T. Murrell, E. S. Driver)
Donald W. Danz (J. W. Fishback, R. E. Johnson, R. A. Gilmore)
Leonard J. Eversull (Frank W. Borman, Francis F. Campbell, Gerald L. Canfield)
Richard E. Gathings (W. D. Baird, R. H. Dana, Sidon Harris, G. J. Long)
George Symonds Glazener (W. R. Mitchell, B. J. Sorrells, Paul Farren)
William S. Granberry (R. N. Bruyere, A. G. Martin, P. M. Thompson)
Mona Dennis Guiler (D. H. Gardner, W. M. Rust, Jr., R. A. Geyer)
Richard Frederick Hagemann (George A. McCalpin, Alfred C. Winterhalter, Lacoste G. Ellis)
Harold Ray Hockaday (K. M. Lawrence, Andrew Gilmour, F. W. Borman)
Winston B. Howard (Lawrence K. Morris, Rudy Sohlberg, Walter Fillipone)

Charles L. Howell (Lynn B. Ervin, R. D. Roberts, Roy Bennett)
Kalman Nathan Isaacs (William B. Agocs, Homer Jensen, Perry Byerly)
Emil S. Johansen (James A. Treybig, C. R. Wallace, Otis B. Hocker)
J. A. C. Keefe (C. H. Green, C. M. Moore, Jr. T. A. Holbrook)
William A. McGarry (Robert A. Gilmore, C. J. Long, Carl A. Willner)
Earle F. Mahaffy (R. B. Ross, T. J. O'Donnell, S. G. Pearson)
E. B. Manchee (Cecil H. Green, F. A. Hale, J. T. Wilson)
Don D. Matson (R. M. Nugent, R. W. Aldrich, J. A. Lester)
Clarkson J. Mayhew (Jackson Young, P. E. Mackey, R. W. Carter)
G. Greer Mogg (B. J. Sorrells, W. H. Johnson, G. E. Fritts)
Tom M. Mount (Robert Baum, K. C. Woodyard, Ben F. Rummerfield)
H. J. Noble (H. L. Voelker, J. C. Porter, R. P. Warren)
Robert R. Parks (H. M. Cooper, Jr., R. E. Davis, J. D. Divelbiss)
George R. Perkins (William W. Clark, Walter E. Martin, Clare N. Hurry)
Lloyd H. Rhodes II (Jack Proffitt, C. J. Long, R. P. Radebaugh)
William J. Robinson (F. R. Kittredge, V. A. Peterson, L. O. Seaman)
J. W. Rogers (Otis B. Hocker, D. T. McCreary, C. S. Johnson)
Halbert Sawyer (R. F. Bennett, S. B. Stewart, D. B. Darden, J. J. Schneider)
Gerald F. Slattery (James B. Macelwane, S. J., Kenneth S. Cohick, John R. Cheney)
B. G. Smith (A. I. Innes, J. O. Laws, K. M. Lawrence)
Sherman Rex Spivey (Cecil H. Green, Paul V. Hodge, Rex H. White)
L. Kelley Turner (E. E. Fickinger, L. E. Whitehead, F. L. Searcy, H. R. Prescott)
L. L. Vaughan (R. F. Bennett, R. J. St. Germain, C. C. Sellers)
Richard E. Whitmore (O. C. Clifford, Jr., C. H. Hightower, J. V. Franklin)
Ben E. Willis (K. E. Burg, Jack Proffitt, R. P. Radebough)
George Henry Zwiebel, Jr. (R. B. Burroughs, W. R. Mitchell, R. E. Klabzuba)

NOMINEES FOR 1956–57 EXECUTIVE COMMITTEE

The following biographical sketches are presented to acquaint members of the Society with nominees appearing on the official ballot which will be mailed to all Active Members in good standing in June. Bylaws Article VII, Section 4, provides that "Prior to June 1, nominations in writing, signed by at least twenty Honorary Members or Active Members in good standing and accompanied by the written consent of the candidate, may be submitted to the President."

ROY F. BENNETT studied electrical engineering at Oklahoma A & M College, Stillwater, Oklahoma. In February, 1929 he was employed as seismic observer with Geophysical Research Corp., continuing until August, 1931 when he returned to Oklahoma A & M to complete his college work. He joined the Independent Exploration Company as seismic observer in August, 1932. While with Independent Exploration he served as seismic observer, seismic and gravity party chief, seismic review interpreter, and geophysical instrument designer. In August, 1945, he became district geophysicist for Sohio Petroleum Company, becoming division geophysicist in 1946, and chief geophysicist in 1949. He organized the geophysical department for Sohio, including gravity and seismic crews, as well as the district supervisory force. He is presently employed as chief geophysicist attached to the general manager's staff in Oklahoma City.

He is a member of the American Association of Petroleum Geologists; Houston Geological Society; Houston Section; Geophysical Society of Oklahoma City and has been a member of the Society of Exploration Geophysicists since 1935. He was secretary of the Houston section in 1948, vice-president in 1949, president in 1950 and district representative in 1951 and 1952.

FOR PRESIDENT

ROY F. BENNETT

KARL DYK

Mr. Bennett served as Vice-President of the Society of Exploration Geophysicists (1954–1955) and was Vice-Chairman for SEG of the New York Oil Finders Convention of AAPG-SEPM-SEG in March, 1955.

KARL DYK received his B.A. degree in Physics in 1929, and his Ph.D. in Seismology in 1934, both from the University of California. During the years following his graduation in 1929, and while studying for his doctorate, he worked with the U. S. Coast and Geodetic Survey, doing research in submarine acoustics. He continued with the Survey until 1935 when he joined Stanolind Oil and Gas Company as a computer on a seismograph party. A year later he was made party chief. He was transferred to Tulsa in 1939, serving as a geophysicist in Stanolind's main office. In 1945, he was made division geophysical supervisor of Stanolind's North Texas-New Mexico division, headquartered in Fort Worth. Two years later, in January 1947, he became supervisor of all of Stanolind's geophysical operations and transferred back to the main office in Tulsa. A year later he was appointed chief geophysicist, the position he now holds.

Dr. Dyk served as Vice President of the Society of Exploration Geophysicists in 1953–54. He is a member of the Geophysical Society of Tulsa, Tulsa Geological Society, American Association of Petroleum Geologists, Seismological Society of America, American Geophysical Union, Fellow of the Geological Society of America, Fellow of the Royal Astronomical Society, and a member of Sigma Xi. He has been a member of the Society of Exploration Geophysicists since 1938, and was General Chairman of the 5th Annual Midwestern meeting of the S.E.G. in Dallas, in May, 1951. Numerous articles by Dr. Dyk have been published in scientific journals, including *Geophysics*, as well as the *Proceedings of the National Academy of Sciences*.

FOR VICE-PRESIDENT

E. V. McCollum

J. P. Woods

E. V. McCollum received his A.B. degree in 1925 and his M.S. degree in 1926, both from the University of Oklahoma. He was employed by the Marland Oil Company from June, 1926, until July, 1929, and by Continental Oil Company as control geophysicist from July, 1929, until May, 1939. He was employed by the Mott-Smith Corporation as chief geophysicist from May, 1939, until September, 1943. Since 1943 he has been associated with E. V. McCollum and Company, gravity and magnetic contractors. He is a member of the American Physical Society, the American Geophysical Union, the Seismological Society of America, Tulsa Geological Society, and the Society of Exploration Geophysicists. He served as Secretary-Treasurer of the Society of Exploration Geophysicists for the year 1948–1949. He served on the Council of the Tulsa Geological Society in 1951–1952, as District Representative of the Geophysical Society of Tulsa 1952–1954, member of the SEG Business Office Committee 1953–1954, and is currently Editor of the Geophysical Society of Tulsa *Proceedings*.

J. P. Woods graduated from The University of Texas in 1925 with the degree of B.S. in Electrical Engineering. He received the M.S. degree in 1930 and a Ph.D. in Physics in 1932 from the same University. From 1933 to 1940, he was in the Geophysical Laboratory of The Shell Oil Company. From 1941 to 1944, he was in the Radio Research Laboratory of Harvard University. Since 1944, he has been Director of the Geophysical Laboratory of The Atlantic Refining Company.

Dr. Woods is a member of the Society of Exploration Geophysicists, the Dallas Geophysical Society, the European Association of Exploration Geophysicists, the American Geophysical Union, and the Seismological Society of America. He is past president of the Dallas Geophysical Society, and is now chairman of the S.E.G. Committee on Publications.

FOR SECRETARY-TREASURER

T. O. HALL

JOHN C. HOLLISTER

T. O. HALL was graduated from Southern Methodist University in 1927 with a B.S. degree in mathematics and physics. Upon graduation, he worked with the late Dr. Robert S. Hyer, president-emeritus of S. M. U. doing electrical prospecting work in South and West Texas.

In 1930, he was employed by Roxanna Petroleum Corporation as an assistant gravity party chief on a torsion balance crew. In 1931, he returned to Southern Methodist University as an instructor in mathematics, at the same time doing graduate work in mathematics and physics. He joined Shell Petroleum Corporation, successor to the Roxanna, in 1933, as a seismologist, working in Louisiana, Texas and New Mexico. In 1938, he was employed by General Geophysical Company as a party chief; promoted to Supervisor in 1940 and moved to Ohio where he looked after crews in Ohio, Pennsylvania, Indiana and Illinois, later moving to Oklahoma. He moved to Houston in 1942, and in 1945, became Vice-President; in 1953 he was made President of General Geophysical Company whose headquarters are in Houston, Texas.

Mr. Hall is a member of The American Association Petroleum Geologists and the Society of Exploration Geophysicists. He has served as President of the Houston Section, Society of Exploration Geophysicists and is a member of the Houston Geological Society.

PROFESSOR JOHN C. HOLLISTER has been Head of the Department of Geophysical Engineering at the Colorado School of Mines since September, 1949. At that time, he left the Heiland Research Corporation in Denver, where he served as Vice President and General Manager, to return to Mines, his Alma Mater (Class of 1932).

Mr. Hollister attended the University of Oregon for one year and then enrolled at Mines in the fall of 1929, completing his work three years later. He joined Plains Exploration Company, Denver, in 1932, as a geophysical engineer, leaving in 1934 to become co-founder of the Heiland Company.

He is a member of Sigma Gamma Epsilon, Tau Beta Pi, Society of Exploration Geophysicists, A.I.M.E., American Geophysical Union, and Denver Geophysical Society. He has served on various committees of S.E.G. and as President of the Denver Society.

ANNOUNCEMENTS

STUDENT CLUBS BOOST ENGINEERING ENROLLMENT

East Lansing.—An organization called *Junior Engineering Training for Schools* (JETS) is bringing the facts of engineering to a growing number of young people and may definitely boost America's race with Russia for trained engineers.

Originated by Michigan State University in 1950, the JETS club program is doing in engineering what 4-H and FFA clubs long have done in agriculture—and with amazing results.

Since the first JETS club was organized in the East Lansing high school in November of 1950, the program has grown to include 75 clubs in 18 states with an active membership of more than 2,000 boys and girls.

A matter of wide concern in America is the fact that Russia is producing about 60,000 trained engineers annually while colleges and universities in this country are graduating 22,500.

This concern was emphasized in the recent report that Secretary of State John Foster Dulles and Atomic Energy Commission chairman Lewis L. Strauss are saying that the long-range security of the country, and perhaps the eventual outcome of the *cold war*, may be basically affected by the continued shortage of scientists, engineers and other technicians.

The working idea for JETS originated with Lorin G. Miller, former Dean of Engineering at Michigan State University, now retired. He believed there should be a *4-H club of engineering* to tell young men and women what engineering is and what opportunities it offers.

"We agreed that the word about engineering was not getting through to the majority of students in high school who are interested in engineering," said M.S.U. Prof. Harold P. Skamser, director of the JETS program today.

"Certainly there are counselors, books and bulletins with information about engineering," Prof. Skamser said. "But very few potential engineers go to these sources and seek out information. We feel that in the JETS program high school students can learn at first-hand the real nature of engineering and be able to compare their talents and abilities with the requirements of the profession."

The 75 JETS clubs in high schools today get this first-hand information through individual and club projects, talks with professional engineers and members of M.S.U.'s engineering staff, and through engineering films and publications.

To help new clubs get started, and to serve all clubs with information and an exchange of ideas, JETS headquarters at Michigan State has built a helpful store of material about engineering. New clubs receive kits listing interesting engineering projects, and a cross-index of more than 100 motion pictures about all phases of engineering are available from industry and other sources without charge.

A club newsletter, "JETS-O-GRAM," is circulated to all clubs and all members receive a handsome metal lapel pin. The specially-designed pins are supplied gratis by a New Jersey manufacturer of engineering equipment.

M.S.U. provides added incentive to JETS members through judging of club projects and a scholarship program. Club members compete with their projects each year for honors at M.S.U.'s big Engineering Exposition. The scholarship program, offered to the outstanding student in each club, covers four years' tuition at M.S.U.

JETS club officials point out that the program is proving effective not only in stimulating interest in engineering but also in another important way: steering some students, who have misconceptions about engineering and whose talents are in other areas, away from engineering. JETS officials believe this effect of the program will reduce engineering *drop-outs*.

These drop-outs, as students who quit school or change their courses of study in mid-stream are called, have been termed *an economic waste* to themselves and the schools already short of meeting the engineering needs of industry. Many educators believe that, too often, engineering drop-outs are caused by students who fail to realize until too late that mathematics and related subjects are musts.

Thus the importance of mathematics and other aspects of engineering are emphasized by JETS clubs in giving students an accurate picture of what the college engineering student must know and do.

Success of the JETS program has brought appeals for information about the clubs from more than 60 engineering schools, engineering societies and industries. That the program is getting results in the clubs themselves is evident in reactions from both teachers and students.

"This is the greatest challenge I have experienced in many years," confided a veteran mathematics instructor and sponsor of a club at Traverse City. "Some of the boys are away ahead of me in their chosen interests and I am amazed at the technical vocabulary they use."

A member of the Okemos, Mich., club has stated enthusiastically: "The JETS club program has exceeded my highest hopes and surpassed anything I dreamed of in benefits to the individual members. It certainly is worthwhile to us as future engineers."

JETS officials believe the program's realistic approach and enthusiastic response is making a real contribution to engineering in America.

OFFICERS OF THE PERMIAN BASIN GEOPHYSICAL SOCIETY FOR THE YEAR 1956
Left to right: R. Maxey Pinson, 1st Vice-President; W. A. Seal, Jr., 2nd Vice-President; L. Decker Dawson, President; Malcolm A Knock, Secretary; and R. J. Knott, Treasurer.

PERSONAL ITEMS

Members of the society are invited to notify the business manager of any changes in their positions or companies for announcement in this section. Members are further invited to check with the public relations departments of their companies to assure that the society is on their mailing lists to receive publicity releases.

JULIAN HAWES is now chief geologist for Crown Central Petroleum Co., Houston, Texas. He was formerly with Sinclair Oil & Gas Co. in Oklahoma City.

C. M. MOORE, JR., president of Geophysical Service International Corporation, will assume the presidency of Rogers Exploration Service Ltd. of Calgary, Alberta. The Rogers firm was recently purchased by Geophysical Service Inc., Dallas, Texas.

J. R. MAXEY has announced that Volume 23 of the Tulsa Geological Society *Digest* (1955) is now available at $2.00 per copy plus postage. Orders should be sent to Mr. Maxey at Box 263, Tulsa, Oklahoma.

ROBERT L. KOVACH, Student member of SEG, has been granted the Stanolind Oil and Gas Company Fellowship in Geophysics ($2,285.00), and is now working toward the master's degree at Columbia University, New York.

HAL J. JONES, director of geophysical research for Texas Instruments Inc., Dallas, is transferring to Houston where he will become chief engineer of Houston Technical Laboratories.

A. P. CRARY, geophysicist of the Air Force Cambridge Research Center, has been assigned to the International Geophysical Year program as project leader of the Antarctic glaciological operations including seismic and gravity surveys, and is now located at the IGY headquarters at 1145 19th St. N. W., Washington 6, D. C.

KARL EWART LEWIS, Active member of the SEG since March, 1936 died last year at Houma, Louisiana where he carried on a consulting practice and was manager of a creamery. Mr. Lewis was a party chief for Geophysical Service, Inc. at the time he joined the society, and later served in the same capacity for Seismic Explorations, Inc., Houston. He is survived by Mrs. Lewis and a son, Karl E. Lewis, Jr. whose address is Box 148, Houma, Louisiana.

PAUL FARREN, formerly vice-president of National Geophysical Co., resigned effective October 1, 1955, after more than eighteen years service with that company, to open a geophysical consulting office in Houston, Texas. The New Second National Bank Building in Houston promised Paul a suite of offices at No. 1528 in the middle of February.

STEFAN VON CROY has been named chief geophysicist for Sunray Mid-Continent Oil Co., Tulsa, Oklahoma.

PETER S. STOUTJESDYK has been promoted from field supervisor to manager of the newly-formed Middle East Division of Geophysical Service Inc., with headquarters in Cairo, Egypt.

R. P. THOMPSON, whose address is Bandera, Texas, advises he has on hand a complete set of GEOPHYSICS from v. 10 to v. 20 inclusive with the exception of v. 11, no. 2; v. 12, nos. 3 & 4; and v. 17, no. 3. He has retired from active geophysical work, and is willing to dispose of his copies.

DAVID S. BAYS has joined the staff of Geophysical Service Inc. as a seismologist specializing in marine oil exploration.

GABOR DESSAU, after retiring in September 1953 from Italian Government service, has continued as "chargé de cours" of Mineral Deposits at the University of Naples, and has from its inception been in charge of the Uranium Prospecting Centre ("Centro Ricerche Minerali Radioattivi") of the ENI-AGIP group. In October 1955 he came to the "Technion" (Hebrew Institute of Technology) in Haifa as UNESCO expert for one year, to advise on the setting up of a Geological Engineering and Mining Department.

J. RYAN WALKER, has been named supervisor for the National Geophysical Company of Dallas, Texas, according to an announcement made this week by officials of the firm. He will make his headquarters in Shreveport, Louisiana.

The appointment of CHARLES M. POWELL, JR. as safety director of Geophysical Service Inc. has been announced by GSI Chairman CECIL H. GREEN.

CASTLE J. HARVEY, head of Texas Pacific Coal and Oil Company's geophysical department since 1953, became assistant manager of exploration, effective January 1. PAUL C. REED of Midland became TP's Chief Geophysicist on that date.

Election of CECIL H. GREEN as Chairman of the Board and election of FRED J. AGNICH as President of Geophysical Service Inc. was announced January 1 by the GSI board of directors.

The action, effective January 1, was taken at the regular December monthly meeting of the board.

Green was elected to the position formerly held by J. ERIK JONSSON, who will devote his full time to duties as president of Texas Instruments Incorporated, parent company of the TI-GSI organization.

C. E. RIDDELL, former Exploration Manager—Northwestern Division for the British American Oil Producing Co., since March, 1953, has resigned as of January 1, 1956 to privately enter general petroleum consulting work in the Rocky Mountain Area. His office will be 1517 Denver Club Building, Denver, Colorado.

RICHARD L. CALDWELL, a member of Magnolia Petroleum Company's Field Research Laboratories, has been promoted to Research Associate. Dr. Caldwell is assigned to and is in charge of the Nuclear Physics group of the Exploration Research Division.

R. L. LAY, Assistant to the Vice President in charge of The Texas Company's Producing Department—Domestic, was appointed Assistant to the Vice President in charge of Foreign Operations—Eastern Hemisphere, effective March 1, 1956.

KENNETH L. COOK, Professor and Head of the Department of Geophysics, University of Utah, Salt Lake City, Utah, has been appointed Chairman of the Mining, Geology, and Geophysics Division and Director ex officio of the American Institute of Mining, Metallurgical, and Petroleum Engineers.

E. D. WILSON has been appointed assistant treasurer for Seismograph Service Corp. in the absence of F. B. LEEDY, the firm's treasurer, while Leedy is on temporary assignment as manager of SSC's operations in Brazil.

HAL R. ADAMS was promoted to Division Exploration Manager, Northwest Division of the Sohio Petroleum Co. in December, 1955.

L. G. CHOMBART has resigned his connection with Amstutz & Yates, Inc., and is now an independent consultant with office at 2215 West Thirteenth, Wichita, Kansas.

EDMUND STUART HASTINGS, formerly with The Texas Company in Los Angeles and Sun Oil Co. in Beaumont, recently joined Phillips Petroleum Co., in Lafayette, Louisiana, as a geologist.

J. E. BONDURANT, of Phillips Petroleum Co., Bartlesville, Oklahoma, has been appointed Treasurer of the Geophysical Society of Tulsa to fill the unexpired term of R. B. RICE who moved to Denver.

The *Joint Directory* of the TULSA GEOLOGICAL SOCIETY and GEOPHYSICAL SOCIETY OF TULSA is now available for distribution. Priced at $2.50 each, copies may be obtained from JOHN J. RUPNIK, 503 Jenkins Building, Tulsa 3, Oklahoma.

HOWARD BRECK, manager of Seismograph Service Corp.'s velocity logging division, delivered a paper at the February meeting of the Pacific Coast Section of SEG. Title of the presentation was "Velocity Logging and Its Geological and Geophysical Applications."

JOHN L. BIBLE, founder and former president of Tidelands Exploration Company, has opened a geophysical consulting office specializing in gravity and magnetic interpretation and supervision. His office is located at 216 West Cowan Drive, Houston 7, Texas.

C. M. MOORE, JR., formerly in charge of Geophysical Service Inc., Canadian operations, has been elected Vice-President. He will maintain offices in Dallas, and will direct GSI's petroleum exploration activities in the Eastern Hemisphere.

As a result of Moore's appointment, expanded duties were announced for Vice-President R. C. DUNLAP, JR. Dunlap, in addition to his present duties as director of U. S. operations, will assume responsibility for Canadian operations. Dunlap will remain in Dallas.

Both Dunlap and Moore have been with GSI for more than twenty-one years.

R. H. WRIGHT, manager of GSI's Southern Division office at Houston, has been appointed Area Manager for Canada, with offices at Calgary, Alberta.

The division post at Houston will be filled by T. P. ELLSWORTH, who has been serving as manager of the West Coast Division. In turn, Ellsworth's position will be taken by J. FRANK FULLER, formerly a GSI supervisor in the West Coast Division. Fuller will have offices at Bakersfield, California.

Herbert Hoover, Jr., Under Secretary of State, will receive Columbia University's Kemp Medal "for distinguished service in geology" at a testimonial dinner on Friday, March 30, at the Men's Faculty Club, it was announced yesterday (Sunday) by Dr. Grayson Kirk, president of the University.

The first Kemp Medal was awarded to the late Charles P. Berkey in 1948. Dr. Berkey was the Newberry Professor Emeritus of Geology at Columbia, and served as geological adviser on the Catskill and Delaware Aqueducts, Grand Coulee and Hoover Dams, and many other important public works.

The second award, in 1950, was received by Dr. Wallace Pratt, formerly chief geologist of the Humble Oil Company, and a widely recognized authority on petroleum.

The Kemp Medal was established in 1947 in honor of the late Professor James Furman Kemp, an internationally known authority on mineral deposits. He was chairman of the Department of Geology at Columbia for many years.

The award committee consisted of Professor Kerr, chairman; Walter H. Bucher, Newberry Professor of Geology; and Marshall Kay, Maurice Ewing, and Charles H. Behre, professors of Geology. In the opinion of the Committee, it is particularly appropriate that the award should go to a geophysicist for the geophysical year 1956.

Prof. Dr. Ludger Mintrop
Honorary Member
January 1, 1956

Rev. Dr. James Bernard Macelwane, S.J.
Honorary Member
February 16, 1956

CALENDAR OF MEETINGS

1956

April

23–26 American Association of Petroleum Geologists, 41st Annual Meeting, Chicago, Illinois
25–29 World-Oil Exposition, Houston, Texas
26–28 American Physical Society, Washington, D. C.
30– 2 American Geophysical Union, Annual Meeting, Washington, D. C.

May

11 Society of Exploration Geophysicists, Annual Meeting, Pacific Coast Section, El Tejon Hotel, Bakersfield, California
11–12 Permian Basin Geophysical Society, Annual Meeting, Scharbauer Hotel, Midland, Texas
17–18 Society of Exploration Geophysicists, Gulf Coast Regional Meeting, Houston, Texas

June

18–24 Acoustical Society of America and 2nd Congress of International Commission on Acoustics IVPAP, Cambridge, Massachusetts (W. Waterfall, 57 E. 55th Street, New York 22, New York)

October

1– 3 National Electronics Conference, Hotel Sherman, Chicago, Illinois
28– 1 Society of Exploration Geophysicists, 26th Annual Meeting, Roosevelt Hotel, New Orleans, Louisiana

November

12–15 American Petroleum Institute, 36th Annual Meeting, Conrad Hilton Hotel, Chicago, Illinois

1957

November

10–15 Society of Exploration Geophysicists, 27th Annual Meeting, Statler-Hilton Hotel, Dallas, Texas

July 1, 1957 to December 31, 1958

International Geophysical Year. (Worldwide) vide GEOPHYSICS, v. 21, p. 257–259.

SOCIETY OF EXPLORATION GEOPHYSICISTS

MEMBERSHIP LIST

February 1, 1956

##Honorary	8
**Life	2
Active	2,921
*Associate	1,716
#Student	255
Total membership	4,902

MEMBERSHIP NUMBERS

Following the name of each member in the alphabetical list is his number, assigned in the order of his election to membership. Following is a list of the assigned numbers by years.

1930–1934	1– 197-4	1946	1778–1911-6
1935	198– 238-2	1947	1912–2050-65
1936	239– 531-4	1948	2051–2427-17
1937	532– 728-1	1949	2428–2785-16
1938	729– 866	1950	2786–3097-22
1939	867– 965-2	1951	3098–3402-43
1940	966–1094	1952	3403–4048-74
1941	1095–1184-2	1953	4049–4798-80
1942	1185–1263-1	1954	4799–5394
1943	1264–1387-2	1955	5395–6129
1944	1388–1629-2	1956	6130–
1945	1630–1777-4		

This list is published from the latest information available to the Society for all who wish to refer to the professional and business affiliations of its members. It is not intended to be used for circularizing or soliciting purposes; information and rates for rental of the current mailing list for these purposes may be obtained from the Business Office, Box 1536, Tulsa 1, Oklahoma.

Any inaccuracies in the list should be reported to the Business Office. Members are requested to report changes in position promptly to the Business Office.

A

ABBEY, G. E. 5507, *Part Owner & Mgr.*, Central Exploration Co., Inc., 2320 E. Central Ave., Wichita, Kan.

*ABBOTT, LT. ROBERT F. 4798-1, Box 419, Class 56H, Webb A.F.B., Big Spring, Texas

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#ADAMS, BUDD B. 5644, University of Wisconsin, Science Hall, Madison, Wis.

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ADAMS, HUGH M., JR. 3458, *Party Chief*, Reliable Geophysical Co., Box 243, Harlingen, Texas

*ADAMS, LELAND C. 2670, *Dis't Expl. Sup't*, Stanolind Oil & Gas Co., 720 Pioneer Bldg., Lake Charles, La.

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ADAMS, WEAVER W. 4155, Sohio Petroleum Co., 1964 W. Gray, Houston, Texas

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ADEN, JAMES D. 4156, *Party Chief*, Coastal Oil Finding Co., Box 261, Carlsbad, N. M.

ADERMAN, C. V. 1494, *Partner-Manager*, Evangeline Seismic Co., Box 1405, Oil Station, Lafayette, La.

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ADLER, L. 197-3, 2540 W. 45th Ave., Vancouver, B. C., Canada

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*AGNEW, HINDS 4091, *Geophysicist*, The California Standard Co., Peace River, Alta., Canada

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AGOCS, W. B. 451, *Geology & Geophysicist*, Aero Service Corp., 236 E. Courtland St., Philadelphia 20, Pa.

AKIN, RALPH H. 2786, *Consultant*, 314 Petroleum Bldg., Shreveport, La.

AKKERMAN, RICHARD PETE 2173, *Geologist*, Gulf Oil Corp., Box 2100, Houston 1, Texas

ALBER, JOHN L. 452, *President*, Bardanal Engineering Co., Inc., 11752 E. Washington Blvd., Whittier, Calif.

ALBERS, WILBURN F. 2427-1, *Supervisor*, Delta Exploration Co., 1234 20 A St., N. W., Calgary, Alta., Canada

ALBRIGHT, E. GLENN 749, *Exploration Sup't*, c/o Richmond Petroleum Co. of Colombia, Apartado 1309, Medellin, Colombia, S. A.

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ALBRIGHT, THOMAS BUFORD 4906, *Seismic Party Chief*, Magnolia Petroleum Co., Box 601, Abbeville, La.

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ALDREDGE, R. F. 1197, *Manager*, Seismograph Service Corp. of Mexico, Ave. Juarez 95-207, Mexico D. F., Mexico

ALDRICH, RICHARD W. 3554, *Seismic Party Chief*, Magnolia Petroleum Co., Box 900, Dallas, Texas

*ALEXANDER, FRANK C., JR. 3675, *Physicist*, Gulf Res. & Development Co., Drawer 2038, Pittsburgh 30, Pa.

ALEXANDER, GEORGE W. 5864, *Seismologist*, Independent Exploration Co., 1922 W. Gray, Houston, Texas

#ALEXANDER, MICHAEL, JR. 4048-1, *Seismic Operator*, Humble Oil & Refining Co., Box 463, Morgan City, La.

ALEXANDER, ROGER G., JR. 6157, *Geologist-Geophysicist*, Standard Oil Co. of California, 10424 S. Portada Ave., Whittier, Calif.

*ALEXANDER, WARREN A. 961, *Research Engineer*, The Carter Oil Co., Box 801, Tulsa, Okla.

#ALGERMISSEN, S. THEODORE 4798-2, Dept. of

Geology, Washington University, St. Louis, Mo.

*ALKIRE, JAMES HENRY 4842, *Geophysicist*, General Petroleum Corp., Box 2122, Terminal Annex, Los Angeles 54, Calif.

ALLEN, CHARLES F. 5509, *Geologist*, Stanford Research Institute, Stanford, Calif.

ALLEN, CLARK E. 4157, *Supervisor*, Geophysical Service, Inc., 522 Arlington Dr., New Orleans 20, La.

ALLEN, FRANK T. 1073, *Geophysicist*, Gulf Res. & Devel. Co., Drawer 2038, Pittsburgh 30, Pa.

*ALLEN, JERRY 5244, *Observer*, Box 1590, Tulsa, Okla.

ALLEN, JOHN LINSLEY 5758, *Geologist*, 6946 Kenwood Ave., Dallas 14, Texas

*ALLEN, RICHARD C. 5510, *Geophysicist*, Petroleum Development Associates, 2510 South Blvd., Houston 5, Texas

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Milstein, Mark
*Nelson, Leonard A.
Nicol, A. J.
*Plouff, Donald
*Roberts, James Everett
Greeley
*Burk, Noel C.
Gunnison
*Sumner, J. S.
Lakewood
*Bowman, Robert
Kretz, R. L.
♯Tomlinson, E. L.
Leadville
*Wells, Herbert C.
Littleton
Sawtelle, Dan M.
Longmont
*Wagoner, Robert E.
Los Animas
Moore, Robert L.
Lowry A.F.B.
*Whipple, Arthur P.

Montrose
Gibbs, Kenneth E.
*Kehoe, Charles A.
Springfield
Crump, William Wade
Walden
Womack, Rex D.
Wheat Ridge
Lomax, C. J.
*Richardson, Daniel W., Jr.

CONNECTICUT

Green's Farms
Zavoico, Basil B.
Ridgefield
Doll, Henri G.
Ferre, Maurice C.
*Gondouin, Michel
Legrand, J. C.
Winsted
‡Angino, Ernest E.

DELAWARE

Wilmington
*Budd, Montgomery R.
*Crabtree, R. W.
Johnson, Norman G.
Lawrence, Robert W.

DISTRICT OF COLUMBIA

Washington
Andreasen, Gordon E.
Barnes, David F.
Bates, Charles C.
Black, Rudolph A.
Brenner, Morris
Brown, C. Bradner
*Byerly, Perry E.
Crary, Albert P.
Henderson, Roland G.
*Heppner, James P.
Hoffer, C. W.
Hoover, Herbert, Jr.
Joesting, Henry R.
Kendall, James M.
King (Miss) Elizabeth R.
Manger, George E.
McGhee, George C.
*Oliver, Howard W.
Pakiser, Louis C., Jr.
Rabbitt, Mary Collins
Swartz, J. H.
Zietz, Isidore

FLORIDA

Coral Gables
Wagoner, George E.
Eglin A.F.B.
*Leaf, Howard W.
Fort Lauderdale
Freeman, Lawrence I.
Ft. Pierce
Shannon, Charles A.
Hialeah
Murphree, Harold F.
Homestead
*Weiss, Ben
Jacksonville
‡Urquhart, Edward H.
Miami
*McCord, J. L.
Opa Locka
Gilmore, Marion H.
Patrick A.F.B.
‡Brereton, Roy G.
St. Petersburg
Sauls, James L., Jr.
Tallahassee
Olander, Amor M.
Shapard, Charles A.

GEORGIA

Athens
‡Bowen, Richard L.
Henkel, John H.
Atlanta
‡Ashton, James D.
‡Bradford, Justin T.
‡Bradley, Edward L.
‡Brown, Newman Holland, III
‡Clarke, Robert Alan
‡Downs, James P.
‡Hogarth, William, Jr.
‡Horn, Leslie J.
‡Michel, Diane
‡Minton, Dennis Charles
‡Scott, William S., Jr.
‡Soderblom, Theodore Wilhelm
Straley, H. W. III
‡Tucker, James Earl
‡Yialamas, A. V.
Chamblee
‡Chancey, C. N., Jr.

IDAHO

Coeur d'Alene
*Hill, D. E.
Glenns Ferry,
*Johnson, R. F.

ILLINOIS

Belleville
‡Uhley, Robert Phil
Chicago
Cronin, Stewart K.
*Stuebing, Richard Hardin
‡Wiggins, John H,. Jr.
Collinsville
‡Bollinger, Gilbert A.
E. St. Louis
McEvilly, Thomas V.
Evanston
Krumbein, Wm. C
Siegert, A. J. F.
*Slack, Howard A.
Mattoon
Dawson, Woodson H.
*Jones, R. H.
Rosaire, C. G., Sr.
Mt. Carmel
Sharp, C. Sheldon
*Stein, Clarke
Mt. Vernon
Rutherford, H.
Roodhouse
*Dunaven, William A.
Springfield
*Spanski, Robert F.
St. Elmo
Adams, Wallace W.
Sidney
Everitt, James
Skokie
*Rutkowski, Chester
Staunton
*Pervinsek, Robert J.
Urbana
‡Gednetz, Donald D.

INDIANA

Bedford
*Bechner, George F.
Bloomington
Blakely, Robert F.
Evansville
Combs, Edward J.
*Slanis, Albert A.
Indianapolis
*McKenzie, Daniel B., Jr.
*Ray, Edward F.
Shelburn
*Downen, John D.

IOWA

Ames
Roy, Chalmer J.
‡Spaeth, Mark G.
Harlan
*Christensen, Fred A.
Iowa City
*Hase, Donald H.
Sioux City
*Tagg, Alden R.

KANSAS

Alexander
*Vague, C. E.
Colby
Hartenberger, R. A.
Scott, M. D.
Fort Riley
‡Blazel, Carl Louis
Great Bend
*Burk, John W.
*Casteel, Hoyt F.
*Chubb, Lewis Orr
*Downs, William M.
Martin, Richard G.
Independence
*Tipton, Dee Leroy
Kansas City
Jones, Harold H.
Lawrence
Hambleton, William W.
Liberal
Staples, Guy W.
*Stewart, Lyle W.
Manhattan
*Bonchonsky, Andrew P.
Meade
‡Bennett, Wesley B.
Callender, Billy R.
Eubank, B. J.
*Mumford, D. Douglas
Overland Park
Guipre, Robert W.
Paola
Phares, Wayne A.
Pratt
Berry, Donald L.
Bratt, Curtis Carrol
Russell
*Richards, Bill A.
Wakeeney
*Bernard, Leonard
Wichita
Abbey, G. E.
Ballard, James A.
Bird, Wesley E., Jr.
*Brooks, Dilliard Lee
Care, John L.
*Cherry, Charles L.
Evans, David Lecount
*Fuqua, Henry H., Jr.
Glover, Robert H.
Henderson, Marion R.
Hill, John Robert
Jennings, J. Paul
*Knight, William V.
‡Lewis, Paul K.
*Mix, Leo R.
*Schaefer, Leo J., Jr.
Trombla, Lynn B.
Van Altena, Peter J.
Wallace, Charles H.
Williams, Charles C.

KENTUCKY

Henderson
Tweddell, Ralph D.
Mayfield
*Evens, Joseph H.

LOUISIANA

Abbeville
Albright, Thomas Buford
Crary, James D.
Mogck, A. R.
Baton Rouge
*Ashman, John L.
Cannon, Mike S., Jr.
*Drews, Theodore E.
Hughson, Barrett B.
Johnson, Byron K.
Kroger, W. L.
Lipscomb, John W.
Parker, Everett H., Jr.
‡Stengel, Eugene
Bernard Parish
Russell, Steward Leo
Crowley
*Blaik, Maurice
*Bourgeois, Alvin J.
*Golson, Rex, Jr.
DeRidder
Whitsitt, C. D.
Donaldsonville
*Blankenship, J. A.
Hammond
Courtney, E. A.
Homer
Sindorf, John G.
Houma
Augustat, George
*Beall, Edward W.
*Cowie, Charles, Jr.
Elston, Chris H.
*Sadler, John W.
*Sole, Lewis
Walton, Paul L.
Jennings
*Jones, Walter Dee, Jr.
Lafayette
Aderman, C. V.
*Bailey, Frank Rose, Jr.
Bell, John W., Jr.
Bennett, Elwin
Boutte, H. G.
*Conley, H. R.
Cramer, Neal Parker
Current, Eugene L.
Daly, W. W.
Darden, David B.
*Dorsey, Mayo B., Jr.
Evans, Joseph B., Jr.
*Fee, Charles F., Jr.
*Fitzpatrick, Harvey J.
Gragnon, Joseph N.
Hargis, A. V.
Harwell, R. B.
Hastings, E. S.
Hazelrigg, James B.
Jeffers, Paul H.
Knight, Fred G.
*Lee, Frank W.
Lee, J. E., Jr.
Martin, Jack P.
Moore, James M.
*Mounce, William Paul, Jr.
Ogden, Roger H.
Ott, Lawrence N.
Palmer, John C.
Reese, W. H.
*Richard, Carl R.
Ricketts, E. L.
*Riley, Louis Ellsworth
*Roberts, Lee Roy
Rowe, Ural A.
*Sawyer, Halbert
Schneider, John J., Jr.
*Schuller, Jerome Albert
Smith, Ralph T.
Spencer, Samuel A.
Standridge, James A.
Tilley, G. E.
*Watson, A. P.
Wells, L. H.
White, William H.
Lake Charles
*Adams, Leland C.
*Auster, Edward C., Jr.
Click, Dean E.

*Donohoe, Henry Thomas
#Dunwoody, Robert H.
Hammons, F. H.
Harrison, James E.
Jones, Thurman L.
*Kersey, Luther S., Jr.
Moore, James A.
*Popp, Frederick Wm., Jr.
Russek, I. W.
Sprague, Robert L.
*Viloni, E. B.

Metairie
Flatley, D. J., Jr.
*Wallace, John J.
Wiley, W. B.

Monroe
Nichols, E. Turnley

Morgan City
#Alexander, Michael, Jr.
*Burrows, Hiram W., Jr.
Bussard, William H.
Gray, C. H., Jr.
Harper, Wilbur L.
*Johnson, James H.

Natchitoches
Harms, James R.

New Iberia
#Greenhagen, Kenneth L.
Knittle, R. B.
*Morrison, Clarence O.
*Nick, Christian J.
*Provensal, Louis V.
*Richard, M. W.
Treybig, B. H., Jr.
*Wambsgans, Richard M., Jr.
*Wilkinson, Reymond W.

New Orleans
*Ackermann, Herbert J., Jr.
Allen, Clark E.
Anderson, Edmund H.
Atwater, Gordon I.
Barker, Alvin F.
*Bell, John H.
*Berry, George F.
*Boebel, Richard Wallin
Brown, L. I.
*Brown, Warren A., Jr.
*Burke, Thomas M.
Burton, Gerald A.
Butler, Robert
Calahan, L. W.
Chalmers, H. B., Jr.
Cobena, L. W.
*Coffeen, James A.
*Coffman, John W., Jr.
Connelly, Roy E.
*Cooper, Edward P., Jr.
*Courtney, Chyde J.
Cowie, Roger H.
DeJournette, R. D., Jr.
*Diment, Wm. H.
*Dingman, Milford H., Jr.
*Dunn, Theodore R.
Duty, W. B.
*Ellis, Earl G.
*Elms, Benjamin M.
*Etnyre, John B.
#Farr, John B.
Frey, M. Gordon
*Funkhouser, Lawrence W.
Girard, Cecil Meshew
*Golosovker, S.
*Green, Wilbur E.
Harang, Jack F.
Harris, J. A.
Harvey, Lyle H.
Hazen, William G.
Holekamp, O. G.
Hutson, Carl Monroe
Jamison, Roy Bland
Kalisvaart, F.
Keese, James D.
King, Billy F.
*Lapointe, Alfred E.
Lilley, Charles C.
*Lucas, Dennis R.
*Mabry, Delord R.
Mann, Neil W.
Markley, Leo A.
*Mason, William V.
*May, T. O.
McCabe, Walter A.
*McCutchen, Edgar O.
*McDonald, Charles R.
McDougall, John E.
*McMaster, J. T.
*Meeks, John F.
Meitzen, J. B.
Morgan, A. L., III
Morgan, George O., Jr.
Murray, Irvin B., Jr.
*Nicholls, Robert Louis
Nutt, Willard Thomas
*O'Connor, Robert B., Jr.
Oudt, F. W.
Petersen, Harluf C.
Pincomb, E. M.
Poirier, O. A., Jr.
Reichert, H. C.
Robert, Kearny
*Rodrigue, L. G.
Samuels, George H.
*Schorre, Barthlome
Shannon, Ellis H.
Sheriff, Robert Edward
*Smith, Darrell E.
Smith, F. A.
Smith, Merrill
Smith, Ross, Jr.
Spiers, James C.
Stone, Robert C.
Stouse, Maurice J., Jr.
Stumpf, L. Beverly
Suggs, Robert L.
Texter, John W.
Upshaw, R. W.
Utterback, D. D.
*Watson, Robert E.
Webster, Felix H.
*Wegener, R. H.
Weis, Robert A.
Wells, Kenneth R.
Williges, William A.
Wilson, David S.
Winters, Rayford W.
Wright, Ronald E.

Opelousas
Ebert, Charles E.
*Eubank, John T.
*Motter, Donald M.

Port Allen
Swearingen, A. C.

Ruston
*Ferguson, Joseph W., Jr.
*Sears, William Earl

St. Joseph
*Reivere, Romaine

St. Martinville
*Hinton, Oscar G.

Shreveport
Akin, Ralph H.
Appendino, John
Baker, Glenn J.
*Barnett, Robert Blake
Barret, Wm. M.
Blevins, Howard M.
Bloomer, P. A., Jr.
*Blubaugh, Norman M.
Boydstun, James A.
*Bradshaw, C. W.
*Bragg, Charles P.
*Browder, Walter Clarence
*Broyles, Robert W.
Bryan, Carl L.
Buckingham, W. T.
Burroughs, B. B.
Butt, Harding
*Bynum, Winifred Wilson
Carter, R. W.
*Chase, Don E.
*Clark, John W., Jr.
Clark, William W.
*Clarke, Clem S.
*Condren, Patton
Cooke, John Graves, Jr.
DeLaune, Henry J., Jr.
*Dinstel, Woodrow L.
Duke, Melvin O.
Eaves, Everett
*Farley, James F.
Ferber, Herbert J.
Ferguson, J. G.
Forgotson, James M.
*Gamble, B. E.
Goebel, Lawrence A.
Grant, Henry Lowry
Harris, John
*Hill, Robert B.
Howard, G. C.
Jameson, John A.
*Jordan, James B.
*Kell, James A.
Kidd, Robert L.
#Lurton, Nelson E., Jr.
Mackey, Patrick E.
Martin, Walter E.
*Mayhew, C. J.
McCullers, Wm. E.
Meadours, James B.
Miller, Sylvestor T.
Morriss, Herbert A., Jr.
*Mount, Thomas M.
Nicholls, Charles W.
Owen, H. J.
*Priester, Willie C.
Proffitt, Jack, M.
Pugh, Moffett L.
Radebaugh, Robert P.
*Reynolds, Pat
*Rhodes, Lloyd H., II
Rosenkrans, R. R.
*Schnieder, Eugene T.
Spradlin, S. T.
Stone, E. T., Jr.
Strange, Booth B.
Tesar, Robert
Teufel, Virgil W.
*Thomas, Roy R.
Thomsen, Erik
*Tilleux, H. O.
Tucker, Bill C.
Wade, R. T.
Wagner, William C.
Walker, J. R.
Walton, Britain W.
Wardell, Richard H.
*Wilhite, W. F.
*Willis, Ben E.
Wilson, Richard M.
Woodyard, K. C.
*Yorston, Howard J.
Young, Jackson S.

Springhill
Gilchrist, William H., Jr.

Thibodaux
Borello, Adolfo Frank
Gabro, Leon H.
*Hunter, Glenn E.
*Lake, Sam R.
*Patterson, Sam W.

Vidalia
*Campbell, Richard A.

Westwego
*Horn, Emmett P., Jr.

MARYLAND

Aberdeen
*Murphy, William H.

Aberdeen Proving Ground
Koenig, Robert J.
Perkins, Beauregard, Jr.

Baltimore
Farnham, Frank C.
#Haines, C. E.
Rim, Herbert G.
Roman, Irwin

Bethesda
Melton, Ben S.
*Romney, Carl F.

Glen Burnie
*Goetz, Louis P.

Havre De Grace
Matthews, Richard H.

Kensington
Balsley, James Robinson Jr.
Doolittle, Russell C.

Owings Mills
Lee, Frederick W.

Silver Spring
Klaasse, James M.
Lipson, Edward
Martin, James M.
Willis, Floyd, Jr.

Takoma Park
Newquist, John W.

MASSACHUSETTS

Arlington
#Walsh, William P.

Bedford
*Fava, James A.
*Goldstein, Norman

Boston
#Pantall, Jack T., Jr.

Brookline
#Orsini, Nicholas A.

Cambridge
#Fink, Don R.
#Grine, Donald R.
#Hallof, Philip
#Hanson, Roy E.
Haskell, Norman A.
Hawkes, H. E., Jr.
*Joyner, William B.
Leet, L. Don
#Lopes-Linares, M.
*Moore, James Robert, III
#Ness, Norman F.
#Neves, Antonio S.
*Robinson, Enders A.
#Rostoker, M. D.
*Simpson, Stephen M., Jr.
#Tooley, R. D.
#Treitel, Sven
#van Zelm Wadsworth, Donald
*Vosoff, Keeva

Danvers
#Leith, Thomas H.

East Weymouth
#Marshall, Donald J.

Jamaica Plain
*Mara, Frank X.

Lexington
#Burrows, Lees J., Jr.

Newtonville
#Madden, Theodore R.

North Adams
*Geiser, David T.

Waltham
Peoples, J. A., Jr.

Weston
Linehan, Daniel S. J.

Woods Hole
Hersey, J. B.

Worchester
*Horner, Robert S.

MICHIGAN

Ann Arbor
Willis, David E.
Wilson, James T.
Detroit
#Cleary, Gerald A.
Mandlebaum, Hugo
Reeves, J. R.
East Lansing
*Vance, T. B.
Houghton
Bacon, Lloyal O.
Longacre, William A.
#Schottlers, George R.
#Tanis, James I.
#Warren, Elmer J.
Ishpeming
Boyum, Burton H.
#Frantti, Gordon E.
*Riedel, Robert W.
Negaunee
*Randolph, E. R.
Ypsilanti
*Clements, Donald H.

MINNESOTA

Buhl
Bickford, Kenneth F.
Minneapolis
Armstrong, Lee C.
Cornell, James R.
*Humphrey, W. R.
Mooney, Harold M.
St. Paul
Wetzel, W. W.

MISSISSIPPI

Biloxi
*Raffalovich, Francis D.
Brookhaven
*Banning, John A.
Barthelemy, J. E., Jr.
Blecker, Julius W., III
Lowery, R. A.
Collins
*Conroy, Richard L.
Columbia
*Langston, B. L.
Lee, Richard E.
Columbus
Bloodworth, Dennis A., Jr.
Crosby
Horn, H. S.
Gulfport
#Murphy, William E.
Hazlehurst
*Smith, Clifton Douglas
Jackson
Allred, Willard A.
Anderson, James W.
Butler, Mark D.
Chang, T. Y.
Cole, Ralph C.
Cook, D. E.
Crager, John A.
Crandall, Robert E.
*Diamond, Paul E.
Duby, Bryan A.
*Fatherree, A. Prentiss, Jr.
Fazakerly, W. B.
*Fleming, Dewitt P.
Forward, Fred
Caby, Ewin D.
Caby, Phil P.
*Graham, Maxwell O.
*Creff, Clarence H., Jr.
Hall, J. A., Jr.
Harris, Holmes E.
*Hinson, Earl, Jr.
*Jones, Sargent F., II
*Kerr, William W.
LeBay, William D.
*Long, Russell L.
MacGregor, J. E.
McDaniel, C. M., Jr.
*Mitchell, James W.
Moredock, John D.
*Myers, M. D.
*Nelson, Robert L.
Ogden, W. Wesley
*Phillips, Cecil Toney
Phillips, Robert
Pretzer, Dwayne L.
#Redish, William L.
Riess, Malcolm
*Robinson, William J.
Smithwick, H. B.
Talmage, E. W.
#Tuller, Bural A
Lexington
*Hughes, Leslie Clifton
Lucedale
Thomas, Ray
Magee
*Jenkins, Allen R.
*Rauschenback, O. J.
*Sigle, Gene C.
Natchez
*Fusso, Joseph W., Jr.
Gulmon, G. W.
Oxford
*Shaw, Maynard D.
Pulaski
*Wicker, John B.
Purvis
*May, John E.
Strakville
Heck, Henry W.
Vicksburg
Callahan, James A.
Waynesboro
*Kwasnicka, Albert F.
West Jackson
*Humphris, Curtis C., Jr.
*Lyth, Ambrose L., Jr.
*Province, Harold E.
*Ramsdell, Jack A.

MISSOURI

Affton
#Scherrer, Robert F.
Joplin
*Brown, Tom T.
*Cash, Robert O.
Kansas City
*Leininger, Robert J.
Linn
*Dessieux, P. Russell
Richmond Heights
#Riley, James T.
#Riley, Robert C.
Rock Hill
#Stolwyk, David J.
St. Louis
#Mansfield, William Adams
#Algermissen, S. Theodore
Blum, Victor J.
*Brys, Eugene Charles
#Chang, Feng-Keng
*Cherry, Jesse T., Jr.
#Daly, Charles M.
#Forrest, Michael C.
#Hasenflug, Harry J., Jr.
#Haug, Ronald E.
Honnell, Dr. Pierre M.
#Leblanc, Rev. Gabriel S. J.
##Macelwane, James B. S. J.
#Mateker, Emil J., Jr.
#Meidav, Tsvi
#Miatech, Gerald James
*Miller, Cecil C.
*Nuttli, Otto William
#Saunders, Barry C.
Scharon, LeRoy
*Smith, Larry W.
*Venker, Donald P.
Savannah
*Yost, Carl E.
University City
Kisslinger, Carl

MONTANA

Billings
Adams, Hal Robert
Allen, Samuel W., Jr.
Armstrong, Orven H.
Bartel, Edwin
*Boyd, Darrell W.
*Bozman, Julius R.
Cioepfil, Gordon D.
Crary, Donald
Crowder, H. V.
Cummins, Dean L.
Davis, J. Lee
*Dean, Julis R.
*Dinkins, Donald E.
*Dix, Max W.
*Fauser, Walter B., Jr.
*Felice, Frank J.
Fellows, Robert A.
*Fox, John F.
Fritz, Edwin A., Jr.
Fruehling, S. W.
Gemmer, R. W.
*Gilstrap, John Samuel
Greenlee, Paul
Grivetti, E. J.
*Harris, Ross Allen
Hoffman, John C.
Hoffschwelle, John W.
Holloway, William L.
*Horn, Wilbur M.
Howe, Ralph H.
Hull, N. L.
*Hunter, Dean T.
Jefferies, Robert L.
*Jodry, Richard L.
Johnson, Melvin C.
Kerns, Clyde W.
King, Thomas C.
Kirby, Gordon
*Langstroth, Ward T.
*Livo, George
Manos, Sammy G.
Marsh, Samuel R.
*Meadows, Harold M.
Menefee, J. C.
Moore, C. F., Jr.
*Naugle, Charles E.
*Newell, James W.
Newton, Austin James, Jr.
*Oakley, William M.
*O'Leary, Timothy D.
*Owen, D. E.
Parker, John M.
*Paterson, Walter D.
Pearce, Warren N.
Penny, Robert T.
Peters, Jack W.
Porter, Hugh, Jr.
Reeves, F. R.
Rouse, John T.
Schombel, Leonard F.
Sides, Joe
*Sonnenberg, Frank P.
*Templeton, James H.
Thirkhill, Edward R.
Thomsen, Harry L.
Wickerham, Maurice D.
Willcockson, James R.
Wilson, E. E.
*Young T. Eugene
Broadus
Marshall, H. D.
Choteau
*Vetten, William
Conrad
*Minton, Richard B.
Cut Bank
Gullickson, W. D.
#Harvey, William L.
*Healy, John C.
*Nay, Virgil D.
*Peffer, John C.
East Glacier Park
Rhodes, Cecil T., Jr.
Great Falls
*Gribi, Edward A., Jr.
Hardin
Floyd, Roy
*Fowler, Frederick B.
Prichard, Harold H.
Harlem
Havener, John H.
Laurel
Robertson, Frank E.
Lewistown
Coleman, Robert V., Jr.
Miles City
Buchner, Harry M.
Colvin, C. E.
Cox, Charles B.
Fisher, Bill M.
*Young, Malcolm Arthur
Plentywood
Canfield, Gerald Lee
Red Lodge
*Bills, Eugene S.
Winnett
Lawson, A. J., Jr.

NEBRASKA

Omaha
Barton, Jackson M.
#Bratton, Robert H.
Sidney
Gillig, Frederick Samuel
Gilliland, J. R.
*Myers, Jack W.

NEVADA

East Ely
Head, E. I.
Ely
Brumbaugh, Harold G.
*Freitag, William G.
Schroll, Charles L.
*Slattery, Gerald F.
Reno
Stephenson, Edgar Lee

NEW JERSEY

Millville
#Williams, Alfred E.
Princeton
*Bonini, William E.
Trenton
#Jablonski, Leo A.

NEW MEXICO

Alamogardo
Jones, Mark W.
Albuquerque
*Birdseye, Henry S.
*Bradford, John Y.
Donnerstag, Philip
*Enyart, Eugene A.
Fishback, Joseph W.
*Jordan, Wilbur E.
Lohse, John M.
#Natwick, Arvid S.
Perret, W. R.
*Radic, Kenneth V.
*Stout, Allison B., Jr.
Westphal, Warren H.
Whelan, Mark
#Young, Durward D.
Aztec
*Coan, G. B.
Copeland, H. V.
McConathy, Warren J.

Carlsbad
Aden, James D.
*Blake, Dale C.
Eastes, William T.
Graham, Floyd B.
Henkhaus, Driscoll A.
Miller, J. W.
*Mitchell, David D.
#*Pratt, W. E.
Witherspoon, Dwayne Russell
Farmington
*Green, James Edgar
*Smith, Wendell R.
Galley
McCoy, G. W.
Gallup
*Chadwick, Curtis Lee
Hobbs
*Coburn, Haskell
Moore, J. Hiram
*Thompson, Grady
Jal
*Andersen, Robert J.
Los Alamos
Cochrane, David W.
Lovington
*Buelow, James W.
*George, Robert G.
*Hunt, J. Richard
*Lambright, Orbie N.
McCuistion, Robert G.
Prewitt
*Colman, Hugh C.
Roswell
*Bollheimer, Paul A.
*Bradley, Robert K.
*Chronister, Bill W.
*Crout, Robert D.
*Danz, D. W.
Files, Wiley Frank
Gilmore, Robert A., Jr.
Hughes, W. R.
Johnson, Richard E.
*Kessler, Eugene L.
Livingston, E. C.
McCoy, William G.
McKenzie, Chessley E.
Molinar, J. J.
Scaife, W. P.
Sheldon, John A.
*Smith, Robert V.
*Spencer, James F.
Socorro
*Gourley, Lloyd E., Jr.
*Holmes, Charles R.
#Kintzinger, Paul R.
#Koger, Robert G.
#McCullough, Edgar J., Jr.
#Meeks, William C.
#Roth, John A.
Vacquier, Victor
Tatum
*Crum, Donald L.

NEW YORK

Amawalk
Kelly, Sherwin F.
Brooklyn
*April, Howard L.
Gabriel, V. G.
*Kelly, Patrick F.
Dobbs Ferry
Clay, Clarence S., Jr.
*Tolstoy, Ivan
Farmingdale
*Nelson, Jerry
Fayetteville
Nash, Cleve C., Jr.
Gloversville
*Brown, Richard W.
New York
#Beckmann, Walter C.
Boyd, James
*Burgunker, Mark E.
Cash, Harvey, Jr.
Cole, E. G.
#Conley, C. D.
Dahlberg, J. K.
*Davit, William A.
Fellows, W. L.
Flittie, Clifford G.
Fryer, Theodore B., Jr.
Gibbon, H. A.
Hafner, W.
Hamilton, G. R.
Hardy, W. W.
Hazen, Geo. H.
Helser, Edwin F.
Kamen-Kaye, M.
Kaufmann, G. F.
*Kettle, Robert W.
Knebel, George Moses
Kogbetliantz, Ervand
Lay, Roy L.
Lopes, Eudes P.
Lynch, J. Joseph, S. J.
*Novotny, Robert T.
Olson, Walter S.
*Rolnick, Leonard S.
*Scott, Robert Franklin
Slotnick, M. M.
Smith, Maurice G.
Thralls, Warren H.
Tucker, Lewis R.
Vajk, Raoul
Van Der Sleen, N.
Wallis, William E.
Whiton, Herman F.
*Withstandley, Victor, III
Palisades
#Davidson, Maurice J.
*DeBremaecker, J. C.
#Drake, Charles L.
Ewing, Maurice
#Heezen, Bruce C.
#Miller, Edward T.
*Oliver, Jack E
#Sutton, George H.
Worzel, J. Lamar
Richmond Hill
Fedukowicz, Waclaw
Scarsdale
*Tarter, Thomas A., Jr.
Syracuse
*Kopka, William
Troy
Beers, Roland F.
#Mercado, Edward J.
Wellsville
*Young, Wilber H., Jr.
White Plains
Hotchkiss, Hugh C.

NORTH CAROLINA

Raleigh
Miller, E. L., Jr.

NORTH DAKOTA

Bismarck
Davidson, David B.
*Garner, Robert E.
Hayes, Quin
*Orcutt, Harry Dale
*Owens, Michael R.
Richardson, Alan J.
Bottineau
Hammond, Dean H.
Dickinson
*Barnes, George L.
*Goin, Milton D.
Fargo
*Light, D. L.
Kenmare
*Nichols, Thomas C., Jr.
Watford City
*Brown, Robert L.
Sackett, L. H.
*Zilik, Roy P.
Williston
Brensing, Vernon Lee
House, J. P.

OHIO

Cleveland
*Begun, Semi Joseph
*Berggren, Charles F.
Birkenhauer, Henry F.
*Kostra, Walter
Walter, E. J.
Columbia
*Mugrage, Eugene Girden
Columbus
Heiskanen, W. A.
*Hickle, William G.
*Pincus, Howard J.
Dayton
Koenig, Palmer E.
#McCormick, Lt. John J.
#Opp, Albert G.
*Smith, Stewart W.
Fairborn
Kaiser, Geo. B.
Findlay
Konkel, Philip M.
*Slough, David A.
Parma
*Miller, Donald M.

OKLAHOMA

Ada
*Hall, Owen B.
*Jones, Bobby C.
Altus
*Franson, Guy W.
Alva
Byrd, Tom W.
Antlers
Olson, Odell C.
Ardmore
*Felix, Charles P.
Jennemann, Vincent F.
*Johnson, Joseph D.
Kingry, Harvey J., Jr.
Kirk, David K.
*Roberts, Paul S.
*Scott, G. L.
#Siegfried, R. C.
*Sykes, Howard A.
Wallace, Bennet Warren
Atoka
*Profera, Joseph A.
*Whitmore, Richard E.
Bartlesville
*Allen, William E.
Bondurant, J. E.
Bradley, R. M.
Courtier, W. H.
Crenshaw, C. C.
Dissler, Ernest W.
Elliott, Sam D.
Ericson, Harry B.
*Graves, John Milton
Hallock, C. E., Jr.
Hintze, A. J.
Johnsen, Harry C.
Johnson, Earl W.
Leisure, John, Jr.
*Lemaitre, Jules W.
McNally, Perry Michael
Mendenhall, Harold L.
Miller, Vincent
Morris, Floyd H.
Myers, James Petty S.
*Naquin, Paul J., Jr.
Piety, R. G.
Rice, R. B.
Rollins, J. C.
*Scroggin, Wendell
Shell, G. Newman
Sparks, Barry M.
Tucker, R. H.
Wolters, Earl M.
Bethany
Anderson, R. G.
Broken Arrow
Hawkins, J. E.
Chickasha
*Gilleland, Kenneth R.
*Harp, Richard C.
*Trammell, Detroy
Duncan
Rusconi, Eugene
Durant
*Turner, Lewis Kelly
Edmond
Jones, Leland W.
Elk City
Levy, Thomas K.
Enid
*Braithwaite, Al
*Caldwell, Walter
Clifton, R. L.
*Fry, William C.
Muir, J. Lawrence
Grandfield
*Nault, Ralph Windell
Henryetta
*Beightol, Richard O.
Hobart
*Smith, Jennings G.
Lawton
#Knapp, Gregory A.
Madill
Salisbury, Thomas R.
Muskogee
Collins, Warren
Cotter, Horace D., Jr.
Norman
#Assiter, Edward J.
*Gaither, Jerrell W.
McGuckin, Glenn M.
Norden, John A.
*Rath, Otto C.
Schriever, William
#Withrow, Phil C.
Oklahoma City
Abbott, Wayne R.
*Anderson, George E., Jr.
*Arkle, John P., Jr.
Baade, John H.
Beebe, B. W.
Bemrose, John
Bennett, Roy F.
*Bickmore, Donald G.
Bleyberg, Arnold H.
*Carmack, Roy P.
*Chenoweth, William C.
#Clinton, R. M., Jr.
Cochrane, John M.
Cody, C. C.
Cooper, Harry M.
Davis, Richard M.
Delbridge, J. D.
*Deupree, Edwin A.
Dudley, R. W.
Dunn, George V.
Ervin, Lynn D.
Fee, S. T.
Foster, John Robert
Gardner, J. W.
Hadler, Harry G.
*Hartman, Frederick H.
*Hewitt, Marvin R.
*Hillery, Robert R.
*Howell, Charles L.
Hurt, Walter L.
*Johnson, Donald E.
Kurk, Edwin H.
*Ledbetter, Charles E.
MacQuown, W. C., Jr.
*Massey, Oris D.
Mayo, H. Bruce
McMahan, Eugene C.
Moore, Delmar D.
Mount, E. L.
Murphy, Boyd F.
*Neece, Neal, Jr.
*Nicholls, Harry R.

Parkhill, J. Brooks
*Peacock, Robert H.
Quay, Roy G.
Quinn, C. J.
Ratliff, D. W.
Roane, W. H.
Roberts, Francis A.
Roberts, R. D.
Robinson, W. Bernard
*Ruminer, Donal E.
Schmalz, Herman J.
Scott, D. L.
Slagle, Walter J.
Smith, Ben Ward
Smith, Cyril B.
Speckhard, W. H.
Stones, J. Eugene
Swan, B. G.
Talley, H. C., Jr.
Thompson, Kermitt C.
Van Nostrand, D. J.
Warren, Paul R.
Witthaus, William K.
Wolff, D. J.
♯Wright, Roger M.

Okmulgee
*Busby, Julian M.
♯Noble, Jack A.

Pauls Valley
*Rogers, Sam R.
*Wilson, George L.

Pawhuska
Barber, R. Curtis
*Richey, Chester Ralph, Jr.

Ponca City
*Barnes, Richard P.
Becker, Adrian A.
Brown, Graydon L.
Campbell, Hollis O.
*Caro, W. B.
Clement, Alvin H.
*Clynch, Frank
*Cobb, Arthur T.
Crawford, John M.
*Doty, William E. N.
Fetrow, John W.
Gaebe, James R.
Gaither, V. U.
Garten, Roy, Jr.
*Gauvin, Gerald R.
Godshalk, D. S.
Goupillavd, Pierre L.
*Hrubtez, Albert
Hughes, Roland F.
Jordan, C. K.
*Laing, Wm. E.
*McGlone, J. F., Jr.
Moody, Herbert H.
*Moxley, Stephen D., Jr.
*Pelton, Charles R.
Pittman, Ross L.
*Richardson, W. E.
*Scheffev, Paul L.
Searcy, Frank
Vorheis, Byron
Waddell, V. H.
*Wakefield, H. A.
Waters, Kenneth H.
Wells, E. L.
Whitehead, Loren E.
*Wissing, Richard Donald
*Witcher, Leland G.
*Zweers, J. R.

Prague
Klabzuba, Robert E.

Proctor
Young, Dewey D.

Purcell
Lee, Claude S., Jr.

Sand Springs
♯Copps, Daniel J. C., Jr.

Sayre
*Houston, Grafton, Jr.
*Ingels, C. Robert
*Veasow, Jack H.
*Wittges, Kurt A., Jr.

Shawnee
Cole, Robert L.
Gibson, G. D.
Hawthorne, W. W.
Lukens, John P.
McDonald, J. Kenneth
Myers, Walter I.
Schaeffer, Hugh C.
Smith, Delbert F.

Southard
*Orlich, Budd

Tonkawa
*Black, Robert J.

Tulsa
Abel, Karl W.
*Alexander, Warren A.
*Allen, Jerry
Andrews, Harry Hugh
Arnold, Tapley G.
Austin, Arthur C.
Ballou, Albert L., Jr.
Baltosser, Robert W.
Barthelmes, Albert J.
Bass, B. L.
Baum, Robert
Bayhi, Joseph F.
Bennett, Owen B.
Bentley-Llewellyn James
Bevan, Thomas J.
Bills, Robert N.
*Bily, James J.
Blakey, Carl W.
*Blaze, William F.
Bonnett, Ibrey T.
Borman, Frank W.
Born, Wm. T.
Boucher, F. G.
*Bowman, D. C.
Breck, Howard R.
Brinnon, W. B.
Broding, Robert A.
Brooks, C. C.
Brooks, W. M.
Brown, Frank E.
Brown, Henry W.
Bryan, A. B.
Buckie, L. S., Jr.
*Bucklin, Charles A.
Buffum, Charles Emery
**Butler, W. W.
Cady, Francis H.
Campbell, F. F.
Catt, James L.
Christy, Robert F.
Clark, R. C.
Clayton, Neal
Clote, Thomas Anthony
Coffin, R. Clare
Collier, John J.
Collins, Elmer L.
Connell, Joe E.
Cooper, Harvey F.
Cooper, Jack
Coryn, F. R.
Cressman, Kenneth S.
♯Crouse, Keith Edward, Jr.
Crumrine, Kenneth C.
*Cunningham, Wm. J.
*David, Roy B.
Davis, D. R.
Davis, John C.
Day, Charles E.
DeGood, R. G.
Dimmick, Opie
*Domenico, S. Norman
Durant, C. P.
Dyk, Karl
*Earthman, James C.
Egan, Daniel G.
Eisler, Joseph D.
Elliott, Jess A., Jr.
*Ellis, Clifton A.
Ellsworth, E. W.
Engle, A. Wendell
Erdahl, William M.
Eshelman, Harry S.
Evans, Julian F.
*Eversull, L. J.
*Farrell, Joseph P.
Faust, Lawrence Y.
Fearon, Robert E.
Fentem, Richard L.
*Ferguson, George F.
Ferguson, Henry B.
Ferguson, John L.
Ferguson, Paul M.
Ferris, Craig
Finley, R. K.
Finn, Robert S.
Fisher, Robert B.
*Fite, W. S.
Foster, Allen
Franklin, John V.
Fredin, David Herbert
*French, John D.
Friendly, Jack L.
Frossard, Robert L.
Garner, J. P.
Garrette, F. I.
*Garrity, T. A., Jr.
Geyer, R. L.
Gilmour, Andrew
Giulio, Stanley E.
Green, R. P.
Green, T. S.
Green, W. G.
Hadley, Charles F.
Hammond, J. W.
Handley, E. J.
*Harlow, Robert O.
Harlton, Bruce H.
Harper, James C., Jr.
Harris, D. B.
Hartline, Ralph E.
*Harwood, Charles R.
Hawpe, F. M.
Heap, Wm. O.
*Heine, Gordon T.
Heineck, Robert L.
Hendricks, William A.
Hickey, J. T.
Hidy, John H.
Hoar, Lorimer W.
*Hobart, Henry M., Jr.
*Hockaday, H. Ray
Hollingsworth, Robert Barclay
♯Houching, Guy M., Jr.
House, A. Maxwell
Howard, Victor, H., Jr.
Hurry, Clare N.
Hyatt, Charles Wm.
Innes, Arland I.
*Jackson, C. Kenneth
Jackson, J. G.
*Jacobson, Rollyn P.
Jameson, Chet H., Jr.
*Jensen, Arnold R.
Jett, Glendon D.
Jewell, David F., Jr.
Johnson, James F.
Johnson, J. H.
Jolly, Richard N.
*Jones, Donald W.
*Jones, Joe H.
Jones, V. L.
Kartman, Douglas J.
*Kelley, William E.
*Keselik, Joseph
Keys, Robert T., Jr.
Kezeler, J. L.
♯Kidd, Donald F.
Kiess, Myron C.
♯Kilbey, Thomas R.
♯Kim, Daniel Yon-Su
Kittredge, F. R.
Knowles, J. G.
Kochendorfer, A. J.
Koeppel, B. W.
*Kornfeld, Joseph A.
*Kosarek, John H.
*Lahmeyer, John D.
Lamb, William C.
*Lambe, John P.
Lamkin, Woodrow W.
Lang, Harold M.
Lash, Charles C.
Lawrence, Clifton C.
Lawrence, Franklin L.
Lawrence, H. W.
Lawrence, K. M.
Lawrence, Wm. P.
Laws, J. O.
Leas, Ruth Rice
Leedy, F. B.
Levin, Franklyn Kussel
*Lisle, George W.
*Lohrentz, Donald
Lynn, Ralph D.
Lyons, Paul L.
*Major, Maurice W.
Manhart, T. A.
Martner, Samuel T.
Marucheck, Joseph L.
Mathieson, Raymond L.
Matthews, W. A.
Maxey, J. R.
Mayes, Tom D.
McAlister, C. H.
*McCaslin, John C.
McCollum, E. V.
McCormick, Max D.
McCracken, Guy I.
♯McKeon, Edward Patrick
McManis, Louis B.
McMillen, Ralph E.
McNatt, E. M.
*Meyer, Robert S.
*Michael, Thomas G.
Miller, James W.
*Miller, L. Ray
Mills, Robert G.
*Molenaar, Joseph P.
Moore, Homer C.
Morris, L. G.
*Morrisey, Norman S.
Mossman, R. W.
Moynihan, C. S.
Nelson, Kenneth E.
New James R.
Newton, George R.
Novelly, Walter O.
Oksa, Donald R.
Oliphant, Charles W.
*O'Neill, John P.
Owen, H. E.
Owen, John E.
Palmer, John E.
Parmenter, H. R.
*Patterson, L. J.
Pelzer, H. L.
Pennington, Wallace E.
Pentecost, Claude D.
Perry, Waynard B.
Peterson, Glen
Peterson, V. A.
Pirson, Sylvain J.
*Poe, Jack W.
Pohly, Richard A.
Pottorf, Newell
Rankin, C. T.
Ransom, J. H.
Reed, David E.
Reed, George W.
Rees, Wesley W.
Reeves, W. A.
Reid, A. C.
Richards, Joseph M.
Richardson, J. W.
Ricker, Norman H.
Ries, John A.
Roark, James J.
Roberts, Price E.
Robertson, K. A.

*Robinson, T. Peyton
Roe, Edward O.
Roemer, C. D.
*Rogers, M. H.
*Rosenfeld, Leonard
Ross, Charles M.
Rummerfield, Ben F.
*Runge, Richard J.
Rupnik, John J.
Rutledge, Richard B.
*Sanders, Raymond
*Sanders, Wilburn L.
Saubert, R. W.
Schedler, George D.
Schempf, Edward G.
Scherbatskoy, S. A.
Schisler, Alvin J.
Schoellhorn, Henry, III
Schoellhorn, S. Wm.
*Seeburger, George B.
*Sheehy, Marshall E.
*Shimer, Gerold J.
Shivers, Grover C., Jr.
Sibley, W. B.
Silverman, Daniel
*Sims, Robert L.
*Smith, Edwin F., Jr.
Smith, Frank B.
*Smith, Keith E.
Smith, W. N. M.
Snow, Leland
Sorge, William A.
Southgate, Tom F.
*Spangler, A. L.
Sparks, Neil R.
Steed, Paul H.
*Sterr, Armond L.
Stover, Edward B., Jr.
Strachan, Clyde G.
Swartz, Charles A.
Swift, Gilbert
Sype, William R.
Taylor, Albert
Taylor, Garvin L.
*Tedder, Joseph Wall, Jr.
Thomas, Lloyd O.
Thomas, T. J.
Thralls, H. M.
*Tibbetts, Arnold M.
Timm, Bert C.
*Townsend, Kenneth S.
Tucker, Paul M.
Van Cleave, R. F.
Vandeventer, Ray B.
*Van Horn, William Hart
Vernon, Jess
Von Croy, Stefan
*Vondran, Robert L.
*Voris, Richard H.
Walton, George G.
*Warren, Howard B.
Watson, Robert J.
Weatherby, B. B.
Weichert, David R.
Weichert, Rudolph F.
Weingartner, R. A.
Weirich, P. A.
Weltsch, E. H.
*Westphal, J. A.
Widess, M. B.
Wilcox, Stanley W.
Williams, Jim R.
Williams, P. S.
Winnek, James R.
Wood, Carroll A.
Woodburn, James E.
Woodward, George Morgan
Zenor, H. M.
*Zongker, Raymond C.
*Zwart, William J.

Watonga
*Scott, John C.

OREGON

Aurora
Lester, O. C., Jr.

Eugene
Duller, Charles E.

Portland
*Seafeldt, Concomly Albert

PENNSYLVANIA

Bethlehem
Gallagher, Robert T.
♯Rayfield, Wayne F.
♯Shelton, Willis S.
♯Smith, James G.

Camp Hill
*Dickson, James A.

Ebensburg
♯Bender, Frederick A.

Gwynedd Valley
*Gross, Richard N.

Havertown
Nahas, Lt. Col. Jack N.

Indiana
*Steetle, David R.

Jeannette
Galpin, Sidney S.

Lebannon
*Harbach, Robert G.

Levittown
Pentz, Harold H.

McKeesport
*Hartman, W. M.

Newton Square
Johnson, F. L.

Norristown
♯Hauschild, Louis W.

Oakmont
Hedberg, Hollis Dow
♯Jarmell, Sol
Smith, Douglas H.

Palmerton
Brubaker, D. G.
McMurry, Howard

Philadelphia
Agocs, W. B.
*Hartman, Ronald R.
*Isaacs, Kalman N.
Jensen, Homer
Smith, George A.
Weeks, Albert W.
♯Wylie, Robert W.

Pittsburgh
Affleck, James
*Alexander, Frank C., Jr.
Allen, Frank T.
Allon, Michael
Bailey, Lothrop H.
Bardeen, Thomas
Carter, R. B.
Copeland, Douglas S.
*Darby, E. K.
*Dean, William C.
Demshar, Ludwig S.
*Duecker, John C.
Durbin, Howard A.
♯♯Eckhardt, E. A.
Elkins, Thomas A.
Fink, Paul O.
*Frankenberger, Zdenko
Gardner, Louis W.
Gealy, Wendell B.
Hammer, Sigmund I.
*Howenstein, Norman Louis
Lugenbill, John M.
Muffly, Garv
O'Donnell, T. J.
Palmer, Alvin Paul
Palmer, Elton M.
Palmer, Loyal D.
Patnode, Homer Whitman
Peters, Leo J.
Reiser, Robert G.
**Ritzmann, O. F.
*Schwartz, Daniel
Scott, J. Lewis
Teague, M. W.
Wardell, John M., Jr.
Watson, George R.
Wickerham, W. E.
Wigbels, Frank B.
Wuenschel, Paul C.
Wyckoff, Ralph D.
*Zacher, Irving C.

South Williamsport
*Wessman, Frederick H.

State College
♯Andrews, Alday B.
♯Cervik, Joseph
Howell, B. F., Jr.
♯Huber, Robert Evans
♯Mathur, Surendra Pratap
♯Smith, Donald Alan
♯Strickler, Donald
♯Wyble, D. O.

Tarentum
♯Goslin, Lewis N.

University Park
♯Watson, Robert J.

Wallingford
Bazzoni, Charles B.

West Pittston
♯Gill, Robert C.

SOUTH CAROLINA

Burton
*Champlin, Jerry B. F.

Johns Island
*Rivers, Lt. j.g. James C. S.

SOUTH DAKOTA

Aberdeen
*Luehrmann, Robert O.

Rapid City
Hastings, James I.

TENNESSEE

Oak Ridge
Banta, H. E.
Garrett, Geo. A.

Winchester
*Matson, Don D.

TEXAS

Abilene
Ashby, Julian C.
Dayton, Morris E.
Grange, Donald C.
*Hewitt, Jack E.
*Jones, Stuart A.
Krejci, James F.
Walling, Ray W.

Alice
Langford, Eldon W.

Alpine
Bevier, Geo. M.

Amarillo
*Felder, Edgar H.
*Hardison, Stanley G.
Kern, Jack C., Jr.
Kilborn, Joseph M.
*Kilborn, Nannette D.
Swords, H. L.

Anahuac
*Campodonico, M. A.

Arlington
Mayfield, Cecil W.

Athens
*McKinley, Wm. D.
*Philbrick, Richard Chester

Austin
Adamson, Wm. H., Jr.
Barnes, Virgil E.
Horton, Claude Wendell
Hughes, Darrell S.
*Lewis, Walter S., Jr.
*McLoud, R. Earl
Muir, David M.
Oliver, Robert M.
♯Powell, Jimmy W.
Reed, Charles B.
White, Clifford E.

Ballinger
Burchett, Charles T., Jr.

Bandera
Thompson, R. P.

Bartlett
Grosse, Will Alex

Bay City
Kemeny, Daniel J.
Lemaster, R. R.
Wadsworth, A. H., Jr.

Beaumont
Bills, Samuel E.
Blanchette, A. J.
Cheesman, Thomas R.
*Christian, Fred H., Jr.
Ellis, L. G.
*Englehardt, James R.
Evans, William T.
Gammon, Orin Rex
Guseman, L. F.
*Hagemann, Richard F.
Henson, Robert L.
Hollingsworth, W. E.
Hopkins, Richard H.
Jantz, O. I.
*Kepner, Thomas H.
Konz, Leo W.
*Lavergne, Arthur J., Jr.
McCalpin, George A.
*Meek, John William
Miller, B. R.
Miller, Thomas F.
Millington, John W.
Mueller, Arno P.
*Noble, Francis H.
Parker, Herbert
*Patrick, William R.
*Perkins, William R.
*Pierce, Russell, Jr.
*Pratt, Raymond
Richert, B. E.
Schroeter, Herbert W.
Smith, Louis M.
*Tiller, Wesley A., Jr.
Weston, Horatio C.
Winterhalter, Alfred
Yeates, F. L.

Beeville
Claunch, E. B.
Jackson, Ralph S.

Bellaire
*Ard, William M.
*Baker, Jerry D.
Butler, Roy
Cowles, Laurence G.
*Crook, Troy N.
*Eckley, Wecley
Frank, Anne R.
Guyod, Hubert
Herzog, Gerhard
Hibbler, Alfred J.
Hubby, L. M.
Itria, Oswald
*Last, Leland A.
Lea, N. J.
Lee, B. D.
Manes, O. B.
McCravey, Leroy
McPherson, Barton F.
Nickerson, Thomas D.
Parker, Kenneth L.
Parrack, A. L.
*Phillips, Jonathan W.
Redding, Vernon L.
Richardson, H. L.
Rogers, Revill M.
Romine, William Lee
Rookus, James D.

Stafford, John A.
Strain, Wm. E.
Sullivan, Daniel H.
Tatsch, O. D.
Treybig, J. A.
Twining, Lawrence E.
Watzlavick, Joseph D.
Wendenburg, Otto
Woolson, John R.

Big Lake
*Erickson, John O.
Shack, William Kenneth

Big Spring
*Abbott, Lt. Robert F.
Barnes, Chester F.
Dahse, Clem A.
*Dick, Charles W.
Gunn, Harry L.
*Kelly, John S.
Larson, G. D.
*Priebe, William Joseph
Wilson, Warren A.

Brady
White, H. Paul

Brenham
#Specht, G. W.

Brownfield
#Evenson, Raymond M.

Brownfield
Holland, Taylor H.
Keffler, Joseph W.
*McKinley, James C.
McReynolds, P. T.
*Wicker, Marshall C.

Brownwood
*Teague, V. E.

Bryan
*Clark, Francis Allan, Sr.

Campbell
*St. Clair, Virgil

Canadian
Wilmot, H. G.

Carthage
*Arnold, Lee K.

Chillicothe
*Bradley, Elbert I.

Cisco
*Porter, C. P.

College Station
#Andrews, Eugene R.
Dehlinger, Peter
#Gregg, Lawrence T.

Columbus
Etheridge, Kirby E.

Corpus Christi
Baird, John Malcolm
Bolinger, John W.
Coffin, Miller G.
Dillon, Bart J.
Finck, Homer C.
Grizzell, Edward I.
Hoover, Lawrence E.
*Hume, Ernest H.
Johnson, Billy C.
Johnson, G. W.
*Low, R. M.
*Mackle, Vincent D.
Macon, Curtis E.
#Maier, Robert H.
Mason, C. C.
*Mayfield, Harold Austin
Megason, Leland G.
*Miller, Dean Hudson
*Nicholson, Ralph C., Jr.
Pfenning, Walter F.
*Speckels, Arthur W.
Teasley, Samuel A.
*Thompson, Norman E.
Wells, R. G.
*Whaley, William J., Jr.
Wood, A. B.
Zazvorka, Jerry, Jr.

Corsicana
#Thompson, Wilbur L., Jr.
*Throop, William H.

Dalhart
*Beam, Richard Allen
*Ganek, Bruce M.
*Wellman, H. D.

Dallas
Acrey, Donald O.
*Adams, Vernie W., Jr.
Agnich, Fred J.
*Albright, Ernest G., Jr.
Alcock, E. D.
Aldrich, Richard W.
Allen, John Linsley
Amis, Walter H., Jr.
*Anderson, Richard C.
*Anderson, Russell W.
#Anderson, William J.
*Andrews, Robert T., Jr.
*Angona, Frank Anthony
Arceneau, J. E.
Arnett, R. D.
Arnold, Kingsland
Ayres, Otis
*Ball, George M.
Bays, David Scott
Bazhaw, W. O.
Bellican, Joseph B.
*Binford, James B.
Blattner, Sanford D.
*Bogart, Bobbie Joe
Bonebrake, Walter C.
Boone, Dan E.
*Boone, James H., Jr.
*Brachman, Malcolm K.
Brantley, L. L., Jr.
*Brennan, Daniel F.
Briggs, George Wendell
Brock, Fred A.
*Brouillette, Etienne
Brown, H. Hallock
Brownscombe, Eugene R.
Burg, Kenneth E.
#Burke, William H., Jr.
Burkhead, Wayne Z.
*Carrow, James O.
*Cash, Floyd L.
Cathey, John A.
*Chamberlin, C. W.
Clewell, Dayton H.
Clifford, O. C., Jr.
Cobb, Howard L.
Collingwood, D. M.
Collings, Francis, Jr.
Conant, E. E.
Conklin, Glen M.
Cornelison, Boyd
Cortes, Henry C.
*Coursey, W. Dudley
*Cundiff, Jerry A.
*Curtis, A. L.
Dahm, Cornelius G.
*Davis, David K.
Deegan, Charles J.
*De Ford, H. L.
##DeGolyer, E. L.
Deloach, E. L.
Dennis, Terence E.
Denton, D. M., Jr.
*Desanto, James F.
DeWitt, Sam N.
*Dial, James B.
*Dixon, H. B.
Dobrin, Milton B.
Dobyns, D. R.
Donnally, Chester J.
Douglas, Jas. Y.
Douglas, Norvel
*Duchscherer, Wm., Jr.
Dugan, Albert F.
*Dunagan, Lillard C.
Dunlap, Henry F.
Dunlap, Robert C., Jr.
Echols, Royce N.
Edmonston, William J.
Eley, James C.
Elliott, Clinton H.
*Embree, Peter
*Evans, Bobby L.
*Evans, Sam L.
Everett, R. D.
#Fagg, David B.
*Felber, Joe F.
Fisk, Frank K.
Foote, Lewis C.
Fordham, Glenn W.
Frasher, James H.
*French, Francis C.
*Frick, Herbert C.
Frost, Holloway H.
Garrett, M. M.
*Garthwaite, Ivan Hiram
Gary, James W.
Gatlin, Maurice Brooks, Jr.
*Gautreaux, Jos. H.
Geer, J. T.
*Gibson, W. Bayne
Giles, Benjamin F.
Gill, John D.
*Gillett, Morris F.
Gillin, John A.
Godbey, Josiah Jernigan
Godbey, John K.
*Godson, Richard H.
*Graebner, Robert J.
Granberry, Harold E.
##Green, Cecil H.
Green, John Wyeth
*Greene, John H.
*Griesedieck, B. H., Jr.
*Griffin, James F.
Griffin, W. Raymond
Griffith, Dale
*Gunter, John R.
Gsell, R. N.
Haggerty, Patrick E.
*Hall, Levi Harvey
Hamm, W. Dow
*Hanna, Ian B.
Harkey, W. J.
Harkness, T. O.
*Harlan, Roger B.
*Harmon, B. F., Jr.
*Harmon, Fred
Hart, Walter S.
Hartley, T. R.
Hazeltine, Harvey M., Jr.
Hathaway, Milton S.
*Hayes, Andrew J.
Haynes, Clifford G.
Heaps, Stanley
Hefferman, William H.
Heilner, Donald Edwin
Herlihy, Daniel E.
Heroy, Wm. B.
Heroy, Wm. B., Jr.
Herr, H. K.
Herrmann, Arthur C., Jr.
Hieatt, Herbert
Hightower, C. H.
*Hines, Harley Frank
*Hoagland, William N.
Hogg, W. B.
Hollis, Jack L.
*Hollis, James T.
Holmes, O. M.
Horn, J. W.
Horn, Russell E.
Howard, George A.
Huber, Bernard H.
Huckabay, W. B.
Hughes, James R.
*Hughes, V. C.
*Hunt, Billy D.
*Hunt, H. B.
Imle, John F.
Isensee, George W.
Ives, Harry Crockett
Jackson, Waldo Emerson
Jasinski, E. J.
Johnson, Lloyd
*Johnston, Edward, Jr.
Jones, Hal J.
Jones, M. P.
Jonsson, J. E.
Jopling, Don W.
##Karcher, J. C.
*Kaufman, Charles S.
Kelly, James Donald
*Kelly, J. J.
Kelsey, Martin C.
Kennedy, Frank H.
Kiesler, Ernest A.
Kimler, Benjamin F.
Kinsley, E. R.
*Knittle, Richard J
*Koetting, Norbert C.
*Latimer, Royce Rea
Lawrence, Philip L.
Lee, Chwan-Chang
*Lee, Ingram, II
Lester, John A.
*Linehan, Alton L.
*Lipscomb, Earl W.
Livingston, H. Raymond
Lodge, James T.
Logue, L. L.
#Lontos, Jimmy Tom
Loper, George B.
Loyd, Edward R., Jr.
*Luehrmann, William H.
*Luker, Robert W.
MacNaughton, Lewis W.
*Malovich, Ernest J.
Mamantov, Ilva A.
Martin, John L.
*Martin, Lucien T.
Mason, J. P.
McBurnett, Harry, Jr.
McBurney, Charles G.
McCain, Hugh, Jr.
McCarver, Holland C.
McDermott, Eugene
McDonal, Frank Jarrett
McFadden, W. A., Jr.
McGehee, Theodore Samuel
McLemore, Ethel Ward
McManus, Jack V.
McMullin, E. F.
McNaughton, D. A.
Miller, Jeff E., Jr.
*Minton, Charles W.
Mitcham, Frank W.
Mitchell, George D., Jr.
Mitchell, W. R.
*Moore, James E.
Moran, Ray O.
Morgan, Chas. Gill
*Morrison, Blackstone L.
Musgrave, Albert Wayne
Mut, Stuart C.
Myers, John R.
Napier, T. S.
Nash, David M., Jr.
Nash, Paul E.
*Neavitt, Kennard I.
Neitzel, Edwin B.
Newton, W. W.
*Noble, Graves E.
Nogami, Henry H.
Opitz, E. E.
Orsinger, Albert R.
Page, John S.
*Parrish, Jerry James
Paslay, L. C.
Paxton, Oswald
Peacock, H. B.
Pellillo, M. J.
*Pennington, Dearyl E.
Pernell, J. H.
Perryman, J. D.
Petersen, Clark A.
*Peterson, James S.
Petterson, Robert W.
*Pflueger, John C.
Pittman, C. V. A.
Powell, Charles M., Jr.
Prickett, Tom, Jr.

*Pritchett, William C.
Rainey, Richard H.
Ransone, W. R.
Reagor, Edward C.
Reedy, Frank, Jr.
*Reeves, James N.
Renner, Darwin S.
Rettger, Robert E.
Richards, David Carl
*Rielly, John F.
Riggs, Emmet Dean
*Roberson, Charles B.
*Rodgers, Joseph P.
Rogers, J. B.
Rollins, J. Frank
Roper, Wm. B.
Rosaire, E. E.
Rose, H. W.
*Rosenbaum, Richard J.
Ruback, Norman
Russell, Dallas L.
*Saliba, David J.
*Sanford, Robert E.
*Scheel, David Robert
*Sell, Wayne E.
Sengbush, Raymond L.
Shaller, Robert B.
Shook, Earley M.
Shugart, T. R.
Shuler, Ellis W., Jr.
Simon, Randolph F.
*Simpson, Edward B.
Sistrunk, John David, Jr.
*Sledge, Thomas Collin
*Smith, Bryan F.
*Smith, Harold D.
♯Smith, Mark K., Jr.
Smith, Randolph
Sorrells, B. J.
Spencer, Morris G.
*Sprinkle, Don L.
*Stanfield, John W.
Stehr, Raymond A.
*Stewart, Alexander T., Jr.
Stewart, Calvin D.
Stripling, Allen A.
Strozier, Orville A., Jr.
*Stuart, Carlton E.
Stulken, Edgar J.
*Swift, Gerald G.
Thomas, Earl
Thomas, John A., Jr.
*Thompson, C. Grant
Thornton, Joseph W.
Tillman, T. H.
Toomey, Eugene J.
Tottenham, W. M.
*Totzke, Frank D.
Towles, Henry C., Jr.
Tripp, R. Maurice
Tronrud, Roy W.
*Tubbs, Kenneth Ray
Underwood, Dale W.
*Underwood, Wayne L.
Utesch, John C.
Van Nostrand, Robert Gaige
Van Petten, Edward E.
Vencil, Sherman L.
*Vetter, Edward
*Wagoner, Marvin L.
*Walker, G. B.
*Walkup, William M.
Waller, J. A., Jr.
*Wallner, Jack D.
Walsh, T. N.
*Walters, C. G.
Ward, Charles J.
Warrick, Thomas R.
*Wentner, Bruce C.
Werth, Henry C.
Westmoreland, Earl E.
Whorton, L. P.
*Willey, John M.
Williams, Floyd J.
*Williams, James L.
*Williams, Ocie G.
Williams, Phil Hampton
Wise, Henry
*Wodrich, Frank W.
Woods, J. P.
Woolley, William C.
*Zalog, Dan R.

Denison
*Foster, Floyd F., Jr.

Denton
*Fulton, Thomas K.

Duncanville
Berry, James E.

Edinburg
*Cross, J. Harvey
Thompson, James G.

El Campo
*Conger, Sidney B.
*Dreves, Jay B.

Eldorado
*Edmiston, Billie P.

El Paso
♯Callaway, Royce L.
♯Cliett, Thomas E.
♯Dean, Alan H.
♯Grant, William D.
♯Hirsch, Harry R.
♯Hunter, Wm. H.
♯Lively, Billy D.
Reed, R. W.
♯Sample, John T., Jr.
♯Scales, Joe H.
♯Wershaw, Robert L.

Ferris
*Winn, Billy

Ft. Stockton
Boyd, Hiram Craig

Ft. Worth
*Acklin, Floyd, Jr.
Aszklar, Stanley J.
Baird, Walter D.
Balbin, Paul D.
Barnum, Warren R.
Bartel, Robert R.
*Baudoin, F. F.
Bell, George A., Jr.
Belt, George R.
*Bledsoe, M. O.
♯Bond, James P.
Boone, William D.
Boring, Burl J.
Bradley, Waring
Brewer, Richard
Callahan, Janie L.
*Clendening, Charles C., Jr.
*Conrad, Gunter W.
Dana, R. H.
*Davis, Billy G.
Divelbiss, James
Diveley, Paul R.
♯Ferguson, John D
Fitts, Mac Elmore
*Flether, Calvin D.
Gemmill, Edward J.
*Greenfield, CliftonOrel
*Greenlee, Darrell Ray
Gullick, Carl H.
*Haggard, Wiley R., Jr.
Harrell, J. G.
Harris, Sidon
Hart, Marlyn R.
Harvey, Castle J. C.
*Hassenfratz, C. A., Jr.
Heggolom, J. Roger
Herron, Robert C.
Itten, H. E.
*Jacobsmeyer, Raymond G.
Johnson, C. S.
Jones, Robert W.
Kerbow, R. B.
Kerr, V. Robert
Krieg, Edward A., Jr.
Laneve, R. O.
Lang, Ralph H.
*Lankton, John M.
Ledyard, Paul H.
Lee, Lynn K.
Lockett, Gwendolyn P.
Lombardi, Leonard V.
Lovejoy, J. B.
Matthews, E. W., Jr.
McCleary, Henry G.
McCreary, Dosh T.
McDavid, P. M.
McKay, A. E.
McKee, Clarence R.
*Mickelson, Kermont B.
Mitchell, Bascom Loran
Morrill, Junis Hughes
Morris, James L.
Mortlock, Frank O.
Munns, Edward J.
Normand, S. R.
Payne, C. Win
*Peacock, James J.
*Perryman, Charles G.
Pilcher, Ned
Prokesh, Hugh E.
Robinson, B. B., Jr.
Rutherford, Robbie Gene
Schouten, F. H.
*Schreur, Harm K.
*Scoggin, Hollis A.
Seaman, L. O.
*Shih, David C. C.
*Simmons, Cal Yates
Singleton, Otho G.
Skinner, John W., Jr.
Smith, G. N.
*Smith, Robert D.
Sprague, H. L.
Strange, O. A.
*Tabor, Leon E.
*Talkington, Gerald E.
Thomas, George L.
*Thompson, Don R., Jr.
*Thompson, H. F.
Traubert, Donald J.
*Turman, Thomas R.
*Van Damme, A. M.
Vastine, Thomas J.
Warren, Kirby J.
Webster, John M.
Wert, Carl M.
*Wesley, Richard H.
Wilson, John H.
*Wilson, John H., II
*Winn, C. L.
Winter, George W.
Woods, Delmer M.
*Zimmerman, Richard A.

Franklin
♯Sheffield, Donald Hinson

Freer
Murphy, John T., Jr.

Gainesville
*Anneler, Joy J.

Galena Park
*Pugh, August Leo

Galveston
*Boyd, Victor C., Jr.
Holder, Homer C.
*Ramey, B. J.

Garland
Oden, A. J.
Stanton, Austin N.

Gatesville
Foote, Richard Q.

Georgetown
*Rader, William P.

Giddings
*Archer, Milton

Gonzales
*Schurig, Fred Max

Granbury
McReynolds, Oliver B., Jr.

Grand Praire
*Hicks, Warren G.

Grapevine
Deacon, L. E.

Greenville
Seiler, George E.

Hamilton
Stiles, Elisabeth

Harlingen
Adams, Hugh M., Jr.
*Buller, Leonard K.

Hearne
Dodd, C. R.
*Hill, Ralph R.

Hereford
*Herr, Wilfred C.

Herman
*Faudry, Ray E.

Houston
*Adams, Alfred W.
Adams, Weaver W.
Adler, Joseph L.
Akkerman, Richard Pete
Alexander, George W.
*Allen, Richard C.
Allen, Stanley R.
*Allen, William Edgar
Allen, Wm. G.
*Amery, George B.
*Ames, Richard F.
*Amos, Delbert T.
*Anderson, John C.
Anderson, John F.
Anderson, Wallace L
Andrews, W. W.
Anthony, James P., Jr
*Armstrong, Vard
Arnett, Richard A.
Arthur, Marion A.
Athy, L. F.
*Avery, Milburn G.
♯Babcock, Walter R.
Bader, Glenn E.
*Baker, Buford M.
*Ball, John Douglas
*Banks, James O., Jr.
Barber, Thomas D.
Barbisch, Joe Bill
Barbour, P. C.
Barclay, Stewart
Barksale, Gerald L.
*Barman, Douglas D.
Bartow, Arthur I.
*Bassinger, William E.
*Bearnth, Robert E.
Beeman, Keith Raymond
Beeth, C. Donald
Bell, Olin G.
Benke, M. L.
Benson, V. K.
Berg, G. A.
Berleth, W. H.
Bertram, A. C.
Bible, John L.
Bingham, W. W.
Bird, Ross H.
Black, J. P.
*Blair, Raymond Harvey
Blau, L. W.
*Bledsoe, W. S., Jr.
Bohannon, Milton A.
Boudreaux, Edward A
*Boysen, Verlon
*Bradley, William
*Branham, W. H.
*Brantley, Robert N.
Bratton, D. J.
Briard, Vernon E.
Briggs, Robert B.
Bristley, Leon P.
Britt, J. A.
*Britton, Donald H.
*Brock, John L.
Brooks, James A.
Brooks, O. D.
*Brotherton, V. J.

Broussard, C. H.
Broussard, D. Frank
Brown, Hart
*Brune, Leroy Charles
Bruyere, R. N.
Bulbon, J.
Bunsen, A. W.
Burkhalter, Howard Lee
*Burkman, Bill C.
*Burton, David L.
Bychok, Victor
Byers, John W.
Cain, James Edward
Campbell, Edmund O.
Campbell, H. H.
Carlisle, Charles H.
Carlton, Dave P.
*Carney, Homer C.
Carter, Paul D.
Carter, Ray K.
Carter, William H., Jr.
Catchings, Robert F.
♯Cengiz, Nick R.
*Chalker, Bruce O.
*Chalmers, F. L.
*Channas, John
*Chapman, Wm. B.
Charrin, Paul J. D.
Charske, Charles J., Jr.
Cheney, Robert H.
Chernosky, Allen A.
Child, V. E.
*Childress, Kay H., Jr.
♯Chism, James W.
*Christman, Albert J.
Clark, George B.
*Clark, Sherman D.
Clark, Vernal D.
Clark, W. C.
Clark, W. O.
*Clifford, Edward Lehr
Cline, Dallas D.
*Cocovinis, D. B.
*Conner, Joseph C., Jr.
Conover, George E.
Conwill, George E.
*Cook, J. P.
Cook, Paul C.
♯Coppedge, D. G.
Cornett, J. R.
Coster, H. P.
*Courtney, Cecil
*Cowart, H. M.
Cram, Ira H.
Crowell, J. H.
*Crusius, Milton Wood
Culbertson, J. A.
Dauphin, W. D.
Davis, Donald M.
Davis, Warren L.
Deussen, Alexander
Dewoody, D. A.
Dexter, Laurence N.
Doe, Robert E.
*Doran, Peter J.
*Doss, Joe
*Dressler, Gene H.
Dunaway, J. H.
♯Duncan, Newton O., Jr.
Dupont, T. F., Jr.
Dupree, Leon L., Jr.
Durapau, Joseph J.
Duty, Robert S., Jr.
*Duval, Ned E., Jr.
Eby, J. Brian
*Edwards, Charles E.
Ehrhardt, Henry L.
*Ellison, Charles E.
Elms, Roger G.
England, C. M.
Evans, E. P.
Farren, Paul
Fay, Charles H.
Feagin, Frank J.
*Feather, J. E.
Feather, W. R.
*Fegan, George K.
*Feist, Wiley R.
Fenton, Harry J.
Ferguson, J. B.
Ferguson, Joe L.
Fielder, Cecil K.
*Finnegan, Michael J.
Fischer, L. F.
Fish, Robert Dudley
Flatow, Tobias
Fleischmann, C. S.
Flude, John W.
Flynn, B. Michael, Jr.
Fogarty, Charles F.
Fohs, F. Julius
*Ford, Wayne T.
*Foster, Frank
*Francis, W. Douglas
Frank, Harold R.
*Frazier, Thomas H., Jr.
Freel, J. F.
Fritts, G. E.
*Foroelich, James E., Jr.
Frosch, Alex
Frost, Noel
Frowe, Eugene
*Fryer, Alan P.
*Funk, Charles L.
Gallaway, R. L.
Gardner, Derry H.
Garrett, Wm. M.
*Garrod, Thomas A.
St. Germain, R. J.
Gerrard, J. A. F.
Gever, Richard A.
*Gibbons, William Dean
Gibson, Wm. H.
Giezendanner, Stuart S.
Gilbert, Gerald G.
Gilbert, Howard J.
Giles, Howard Windfield
Gill, O. P.
♯Gilliland, Robert E.
*Girard, Harry J.
*Glazener, George S.
*Goddard, Douglas D.
Goedicke, Thomas R.
Goldstone, Frank
*Gorman, D. Y.
Goss, Henry V.
*Grafton, W. Dean
Graham, John R., Jr.
*Granberry, William S.
Grant, Colin K.
*La Greca, S. A.
Griffin, Irving M., Jr.
Grunebaum, Bernard
*Guiler, Mona Dennis
*Hachenberg, Charles D.
Hagen, Cecil
Haggard, S. E.
*Hajovsky, Henry J.
Hale, Edward M.
Hale, R. B.
*Hall, Ernest M., Jr.
Hall, O. W.
Hall, T. O.
Halliday, Otis T.
Hamil, A. B.
Hamill, Robert M.
Hamilton, W. Brooke
*Hammial, Le Roy L.
*Hammons, Reve H., Jr.
*Hanahen, P. M.
Hans, Edward Walter
Happel, Henry H.
Happel, Henry H., Jr.
*Harbaugh, Allan W.
*Harbison, Reginald N.
*Harding, Norman
Harkins, Curtis P.
Harkins, T. I.
Harper, William Earl
Harrington, G., Jr.
*Hartin, Curtis L.
Hartman, Jack T.
Hatcher, Stanley A.
Hawes, Julian
Hawes, W. S.
Haynes, Cecil J.
Hays, Clyde L.
*Heacock, John G., Jr.
Hebert, Harold C.
*Hegar, Daniel Theodore
Heggy, Homer L.
Heintz, Karl O.
Hemmi, C. W.
Henderson, Homer I.
Hendrickson, F. Victor
Hermont, Alfred J.
Hessi, William R., Jr.
Hibbler, M. E.
Hill, E. Bruce
Hill, Joseph Weldon
Hillery, Robert D.
Hinson, Cecil C.
Hoard, J. O.
*Hobbs, Willis Ezra
Hocker, Otis B.
Hodge, Paul V.
Hoeninghaus, F. A., Jr.
Hohlt, Richard Bozman
*Holland, Edward H.
*Holland, Richard R.
Holland Sam B.
Holmberg, Jean M.
Hoover, H. L.
Hoover, J. W.
Hope, Ray
Horvitz, Leo
Howard, Ben R.
Howard, R. C.
*Howe, Paul E.
Howell, Lynn G.
Howells, Fred W.
Hubbard, Charles L.
Hubbert, M. King
Hubner, Bernard G., Sr.
Hudman, Vernon C.
Hudson, Frank W., Jr.
Hudson, James Davidson
*Huffman, Charles H.
Hull, J. W.
Hunzicker, A. A.
Hurt, Worth B.
Hutchinson, C. C.
Ivy, John S.
Jackson, G. L.
Jett, J. E.
*John, Fred Samuel
*Johnson, Dean
Johnson, J. R.
Johnson, W. D.
Jones, E. E.
Jubran, Joseph R.
Judson, Sidney A.
Kannenstine, Fabian M.
*Karlskind, Don B.
Kaufman, Sidney
Keeling, Richard Wilson
*Kelly, Robert W.
*Kemp, Robert Eugene
Kendall, John M.
Kennedy, Robert P.
*Kenney, Teddy R.
Kent, Harold E.
Kent, Leon A.
*Kepner, James H.
Khan, Riaz H.
Kimball, W. C.
Kimes, Albert
*King, Victor Hugo
Kisler, Floyd
Klaveness, Alf
*Knight, Joseph C.
Knouse, Anthony M.
Kohler, A.
Kokesh, F. P.
Kouri, Barton H.
*Kovar, Merle David
Krause, Fred W.
Kriegel, H. C.
*Kringel, Howard E.
Kubik, Kasmier D.
Kunkel, Turner L.
Ladner, A. L.
*Laker, John D.
Lamb, Geo. B.
*Lara, Rolando
Larue, J. E.
Lau, Frank W.
*Lavender, Gerald J.
Lawhorn, O. T.
*Layton, Wiley Fred, Jr.
Lea, W. T.
*Lee, Thomas S.
Lee, Walter B., Jr.
Leonardon, Eugene G.
Leventhal, Stanley M.
Lewis, Ray C.
Lewis, Wendell L.
Lipson, Leonard B.
Locke, Edgar R.
Long, Gebhard J.
Love, Kenneth E.
Lovett, Don G.
Lowther, John E.
*Lundstrom, Fred L.
*Lynch, Vance Milton
Lytle, T. M.
MacAllister, C. T.
Mace, G. M., Jr.
*Malicoat, William Marcel
Malone, Edwin A.
Mann, Ralph W.
Mannes, W. H.
Marr, John D.
Marsh, Albert P.
Marti, E. J.
Martin, Arthur G.
Martin, Bob J.
Martin, E. C.
Martin, Sidney A., Jr.
Martyn, Phil F.
Mather, W. Scott
McCann, K. G.
McClure, C. E.
McCollum, Burton
*McCubbin, Roy H.
*McCullagh, John, Jr.
*McDonald, William R.
McDonnold, H. W.
McDowell, A. N.
*McDuff, Milton A.
McElree, George D., Jr.
McFerron, George I.
McGee, John E.
McGowan, F. H.
McKelvy, W. H.
McLoad, Kenneth W.
*McNeill, Walter A.
McReynolds, Gregg F.
*McWilliams, Donald G.
Melchior, Louis F.
Melton, D. P.
*Miles, J. R.
Miller, Arthur Barrett, Jr.
*Miller, Charles M., Jr.
*Miller, Thomas J.
Millet, M. J.
Mize, Doyle D.
*Mogg, George Greer
Monkhouse, John R.
Montgomery, George P., Jr.
Montgomery, J. C.
*Moore, John H.
Moore, R. R.
Morris, H. B.
Morton, A. G.
Mott-Smith, L. M.
Mounce, W. D.
Mower, L. K.
*Murray, Edward F., Jr.
Murrell, James T.
Nance, A. G.

Nash, John P., Jr.
Neff, W. D.
*Neill, Calvin F.
Nelson, James K.
Nelson, William P.
Nettleton, Lewis L.
Newby, C. J.
Newton, William H.
Nichols, James B.
Nicolai, Fred Henry
Nixon, Robert F.
Noonan, W. H., Jr.
*Nordling, Robert W., Jr.
*Norman, Isaac W.
*Norman, Robert
*Novak, A. J. W.
*O'Connor, W. H.
*Officer, Charles B., Jr.
#Olson, Alfred D.
Olson, Robert W.
Ording, J. R.
Ostreim, Russell N.
*Outcalt, Earl E.
*Pace, James R.
Paitson, Lloyd
Palmer, Oscar M., Jr.
Palmer, Robert L.
Pardue, George H., Jr.
*Parker, John C.
Parker, L. A.
Parker, Richard H.
Paschall, John P.
Patrick, Homer G.
Patterson, Harold F.
*Paul, Kenneth W.
Pawley, Julian K.
*Payne, William E.
Pechacek, Emil F.
Pemberton, William Dwight
Pena, Sam M.
Phelps, Kenneth D.
Phillips, Gerald C.
*Phillps, Mary S.
*Pick, Albert L.
#Pickett, Geo. R.
Pierson, Andrew Luke, III
*Pierson, Jack N.
Pilcher, Ted
Pittman, R. R.
*Pitts, J. B.
*Poindexter, Joe L.
Poindexter, Louis M.
*Poland, V. K.
Pollard, J. C.
Pollard, William
Pope, Thomas T., Jr.
Postma, G. W.
Powell, Paul B.
Pranglin, John A.
Prator, A. T.
*Prator, Miles D., Jr.
Pratt, Ernest A.
Prescott, H. R.
*Price, James A.
Pruitt, M. F.
Rabensburg, Aubrey H.
Randolph, James R.
Ray, Robert H.
*Reed, Brattie G.
Reed, Chas. F.
Reid, William, Jr.
*Reinhardt, Alvin C.
Remick, David B.
Reynolds, F. F.
Rhodes, Joseph Stockton
*Rice, Paul
Richards, George Leroy
*Rieker, William J., Jr.
Riendl, Joseph A.
*Riley, James K., Jr.
Robinson, Charles L.
*Robinson, Edwin H.
Roesch, Robert C.
Rogers, Austin S.
Rogers, L. Brann
Rogers, Sam D.
Rolshausen, F. W.
Romberg, Frederick E.
Roos, Lewis V. S.
*Row, Duane W.
Rulfs, G. W., Jr.
Ruska, Walter E. A.
Rust, W. M., Jr.
Sagoci, Hilmi F.
Sanders, C. W.
*Sanders, George
*Sandlin, H. L.
Sappington, Chester
Sargent, R. L.
Sasseen, John H.
*Sax, William A.
Schafer, Sidney
Schander, J. R.
*Schildkraut, Jack
Schmidt, Henry
Schmuck, Rudolph H.
*Schneider, J. W.
Schofield, G. A.
Schuchardt, Glynn M.
Schulte, Winston H.
Schumacher, J. P.
Sears, Harold A.
Segal, Jerome Joe
Selig, A. L.
Sellers, Blake M.
Sellers, Charles C., Jr.
Sellers, Clemille Franklin
Seriff, Aaron J.
Sheets, Martin M.
*Shelhamer, LeRoy C.
*Shell, W. E.
*Shepperd, William M.
*Shera, Frank White
Sherar, E. S.
Sherar, Stuart
Shimek, E. Joe
Shore, Harold F.
*Showalter, Richard C.
Simmons, Alvin E.
*Sims, Sam E.
*Sinclair, Kenneth C.
Sisson, Harry H.
Smith, A. E.
Smith, Aylwin L.
Smith, George R.
*Smith, Gilbert M.
*Smith, Glenn C.
*Smith, Harold B.
Smith, H. C.
Smith, J. Angelo
Smith, Neal J.
Smith, Noyes D.
Smith, Roy O.
Somers, George B.
Speed, Carleton
Spencer, Jean S.
*Stallings, Billy M.
*Stanford, Earl Brock
Stanley, Leycester
Stanley, Olan W.
Stauffer, Arthur L.
Steele, Wm. E., Jr.
Van Steenbergh, S. K.
Steenland, Nelson C.
*Stephens, Lester H.
Stewart, S. B.
Stommel, H. E.
Stone, George B.
Stratton, Everett F.
Stuever, Theodore J.
*Summers, Frank Bailey
Summers, G. H.
*Sundt, Peter C.
Swanson, Marion T.
Sweet, R. C.
Taylor, Josiah
Taylor, W. H.
Teague, Norman P.
Terrasson, Paul Louis P.
Terry, Melvin C.
Terry, Russell D.
Thackston, Warren C., Jr.
Thomas, Dick L.
Thompson, Paul M.
Thompson, R. R.
*Tinsley, Arthur B., Jr.
Tippie, Frank E.
Todd, James H.
*Toliver, Billie A.
Tucker, Robert L., Jr.
*Tuman, Vladimir S.
Turney, Maurice D.
*Urban, L. M.
Utter, Richard E.
Van Auken, John A.
*Van Dusen, M. D.
Van Melle, F. A.
Van Siclen, DeWitt C.
*Vaughan, Leslie L.
Vernon, George H.
Vogel, Charles B.
Vreugde, L. M. H.
Vreugde, Th. L. J.
Wahl, Carl C.
*Waldie, Alan D.
Walker, James E.
Wallace, C. R.
Wallace, F. Ritchie
Wallace, James L.
Wallis, William S.
Watt, J. S.
*Weaver, Earl M.
##Weaver, Paul
Webb, James F., Jr.
Webb, Kenneth
*Weber, John D.
Weisbrich, R. A.
Welboan, J. S., Jr.
*Welch, Margaret Marie
Wendenburg, C. F.
Wendler, A. P.
*Weston, Ray Franklin
*Weyand, Jack C.
*Wheat, James M.
*Whitcomb, Harry S., Jr.
White, Gale
White, S. A.
*Whitten, Stephen E.
Wier, Joe R.
Wilber, Roscoe C., Jr.
Wilcoxon, Robert B.
Wilkens, Lucian Minor
*Williams, A. Paul
Williams, C. E.
Williams, E. Darrell
*Willis, David G.
Wilson, James M.
Winston, Val G.
Wolf, Alexander
*Wolfgang, James L.
*Womack, H. O.
#Wood, John D.
*Woodham, Billie A.
Worden, Sam P.
*Wottlin, William O.
Wright, Fred E.
Wright, Ray H.
Yokubaitis, A. C.
Zagst, Edward F.
Zimmerman, C. C.
Zirbel, N. N.
*Zwiebel, George H.

Irving
Batson, James B.
*Campbell, William M.
Swafford, Thomas W., Jr.

Jacksonville
*Ragsdale, Dixie M.

Kenedy
*Kay, R. E.

Kermit
Burt, W. H.
Daly, T. E.
Smith, Edward F., Jr.

Kingsville
Hunt, E. W.
Kale, Henry W.
Minturn, Henry C.

La Marque
Parke, Morton L., Jr.

Lamesa
*Benson, Herbert N.
Christensen, Marlin H.
*McCurdy, John C.
*Scott, Clarence E.
Wigley, Lawrence H.

Levelland
*Heard, James R.

Lockhart
*Bernard, Curtis R.

Lockney
Thomas, Virgil O.

Longview
Majure, Robert S., Jr.

Lubbock
*Blum, Harold A.
*Gilbert, Kennis W.
*Hilburn, James O.
Hodgson, Roger K.
*Hughes, John C.
Klaus, H.
Lamm, Robert J.
Logan, W. B.
Lusk, J. C.
Morrison, Malcolm S.
*Moss, Clellen G.
Novotny, J. D.
Richardson, H. K.
*Sanders, Raymond L.
Smith, C. C.
*Smith, J. O.
*Valder, Clayton S., Jr.

McAllen
Fallin, J. A.
Harris, B. A.
Moore, F. A.
*Weyer, John F.

Mercedes
Jameson, W. W.

Mexia
Turner, Gerald L.

Midland
*Andrews, Stanley M.
Armstrong, John Moore
Atchison, Carl H.
Baile, Richard A.
Bailey, J. J.
*Barker, Addison S.
Barnes, A. L.
*Beard, John G.
*Blakeman, Edmund R.
Borys, Edmund
Breedlove, Ruth
*Brownwell, George S., Jr.
Burton, Raiford H.
*Cartwright, Jack C.
*Collier, M. E.
*Compton, Lee
Cornell, Russell B.
Cornish, Lou G.
Daly, John W.
Dawson, L. Decker, Jr.
DiGiulio, Fred J.
*Drachenberg, William A.
Early, Paul M.
*Edwards, Jack W.
Epperson, Louis J.
Faubion, Charles G.
Feather, V. G.
Fennessy, William J.
Fickinger, Elwood E.
*Filson, H. F.
*Finley, J. E.
Fischer, Leon
Fisher, Guy W.
*Foster, Aaron F.
*French, John Randolph

*Gaines, Betty
*Gall, Jeanette H.
Gibson, George R.
Goodenow, Wayne B.
*Goodfellow, Robert T.
Grimm, G. A.
Hake, Stanley L.
Hammel, Warren R.
*Heidt, Arnold, Jr.
Hendrix, Clyde E., Jr.
Hinton, B. H.
*Holt, Thomas C.
Homan, W. L.
Horton, J. D.
*Hovey, Gene D.
Ittner, Frank
Ivey, James R., Jr.
Jackson, O. B.
Jasper, Walter E.
Johnson, Lester H.
*Johnston, Jerry B.
Jordan, Eaton A.
Knock, Malcolm A.
Knott, Robert J.
Lago, Nils
*Lamont, William Alexander
Lawson, Royce E., Jr.
*Ligon, W. H.
Long, Clarence J.
*Marcusson, Melvin B. L.
Martin, G. W.
Mason, Marshall Lee, Jr.
McFarlane, John F.
*McGarry, William Andrew
*McKeever, Carl Daniel
McMahan, J. R., Jr.
Mehringer, A. P.
Mercier, Vincent J.
Michaelson, L. H.
Miller, R. D.
Mims, Robert L.
*Miser, H. T.
Moore, Arthur A., Jr.
Morehead, Jack N.
*Neill, Everett D.
Nixon, R. A.
*Noble, Hubert J.
Nugent, R. M.
O'Brien, William R.
Owings, B. F., Jr.
Ownby, Byron G.
*Padgett, George E., Jr.
Page, C. Newton
Park, Lee B.
Park, Noel Robertson
Partridge, Chester R.
*Patch, James R.
Patterson, W. L.
Peacock, Elwin M.
Percy, C. G.
*Phipps, Rollin E.
Pinson, R. Maxey
Pluta, Joseph S.
Pohle, Ronald E.
Porter, James C.
Ray, Lilburn B.
Reed, Paul C.
Reel, Cecil E.
*Rogers, James W.
Ross, W. T.
Rumsey, Paul T.
Rustamier, Jack W.
St. Clair, Donald W.
Schneider, W. T.
*Schubert, Raymond Donald
*Scudday, Edwin R.
Seal, W. A., Jr.
Shamblin, W. E.
*Shettle, George O.
Shock, Lorenz I.
Shoup, George Joseph
Singer, Robert R.
Smith, Stanley L.
Smith, William O.
*Sorgenfrei, D. C.
*Spalsbury, William A.
Spence, James F.
*Swanson, Jack G.
Templeton, Harvard G.
*Thompson, Roy W.
*Tift, S. W.
*Tool, Myrtle Alice
#Troseth, Frank P.
Trostle, Maurice E.
Turner, Dale E.
Ubrig, Leonard F.
Unger, E. E.
Vanderdoes, George Glenn
Walker, Wm. N.
Wallace, Menta F., Jr.
Ward, Joe H. E.
Warren, R. P.
*Washburn, James C.
West, James L., Jr.
Williams, Thomas H., III
Winter, Niles B.
Woods, Douglas James
*Wright, Jesse W., Jr.
Wright, Randolph E.

Mineola
*Thompson, H. L., Jr.

Mission
*Lloyd, Claude I.

Monahans
*Balzer, John W.
*Dawson, Gilbert E.
#Drake, Don F.
*Jameson, William H.
*Krivoy, Harold L.
Newman, C. E.
Watts, Evan

Morton
Ellis, Owen C.

Muenster
#Hamric, Burt E.

Normanna
#McMurry, Melville B.

Odessa
*Broman, William H.
Davis, L. A.
#Gilliland, Don T.
*Igou, D. L.
*McAnally, Donald E.
*Scofield, Louis M.
Sims, Elmer R., Jr.
Thurber, Charles H.
Walling, F. Rex, Jr.

Orange
*Gregory, Richard R.
Habr, Frank J.
*Hargest, Thomas Sewell, III
*Lewis, George W.
Mace, H. G.
Marlin, John L., Jr.
Maureira, Artemio S.
*Smith, Donald Raymond
*Williams, Bradley Fredrick

Ozona
*Kaukonen, E. K.
Seim, Carl H.

Palestine
*McGiboney, James C.
*Newton, Robert A.
*Parker, Marion Hamlett
Williams, Richard

Pampa
*Heil, Charles G.
*Yelken, Jack H.

Paris
*Green, Charles Wheeler

Pasadena
*Greene, Eugene F., Jr.

Pellaire
Lueth, Clinton A.

Perryton
*Harvill, Robert S., Jr.
*Kent, Robert F.
*O'Connor, Michael James
Thomas, Phil Howard

Port Arthur
*Kruppenbach, John A.

Port Lavaca
*Kitzman, A. C., Jr.

Rankin
Friday, Marion T.
*Livermore, Howard W.

Richardson
Mayes, Fred M.

Richmond
Blair, John F.

Rockport
*Littlefiels, B. E., Jr.

Rosenberg
*Brogden, William I., Jr.
Deaver, William W.
*Foote, W. L.
Myers, Charles E.
Neese, U. E.

San Angelo
*Beesley, Stratton W.
#Blum, Clement J.
*Clemens, Augustus D.
*Green, Howard W.
Handley, Ed M.
Kimbell, Charles L.
Rabensburg, N. J., Jr.

San Antonio
Allen, Thomas L.
*Bell, Clifford O.
Cook, John C.
Crawford, Paul D.
Crawford, Weldon L.
Dawson, Herbert M.
*Dinkins, H. H., Jr.
Donnelly, V. T.
*Downs, J. W.
Edmonson, J. W. E.
*Felcman, Frank L.
Frazier, Dillon Schadt
#Frazier, Meriwether L.
#Fritz, Joseph F.
Hannum, Wm. L.
*Henkhaus, Weldon C.
*Howell, John L.
Hunzicker, Vernon J.
Kelley, Ward W.
Koenning, Eddie Lee
*Langwell, August III
Mayne, W. Harry
McClellan, Oliver
*McInerny, J. W.
*Moody, James L.
Moore, Marion J.
Moore, W. Lee, Jr.
Narvarte, P. E.
*Nigh, Clarence R.
*Norman, Clarence D.
Ohman, John
Parr, J. O., Jr.
Petty, Dabney E.
Petty, O. Scott
Petty, Van A., Jr.
Phillips, Clifton
Pratt, R. B.
#Proctor, John L.
Quarles, Miller W., Jr.
Rudolph, P. J.
Schmidt, K. H., Jr.
Smyrl, H. B.
Snyder, Charles W.
Souther, J. B.
Stephenson, Lawton Blaine
*Stieren, Jack
*Vidrine, Charles B.
West, Thomas S.
Wright, J. Dexter
*Wu, Chang Sheng

Sanderson
Davidson, G. B.

San Marcos
*Bales, Henry R., Jr.

Schulenburg
Ehlert, Gilbert W.
*Winter, Laurel Q.

Seguin
Blumberg, Roland K.

Selsbee
*Mitchell, Robert L.

Seminole
*Blackwell, J. A., Jr.
Epperson, R. S.
*Smith, Billy G.
*Sparks, James W.
*Venters, John B.
#West, Francis G.

Seymour
*Reilly, L. E.

Shamrock
*Beall, John R.
Clark, K. M., Jr.
*Orlansky, Ralph

Sherman
*Guyton, William H., Jr.
Schiflett, H. L.
*Smith, Howard Leonard

Sinton
*Agerton, William D.
Larue, Wilton W.
*Ramzinsky, G. D.
*Sharp, John H.
Stacy, E. L.

Spearman
Forbes, C. B.
Preston, B. G.

Stamford
Pitts, J. J.

Sweetwater
*Bralley, James M.

Temple
*Tyroch, Henry A.

Terrell
Haynes, R. B., Jr.

Three Rivers
*Harmonson, John R.

Tyler
Anderson, Owen William
Arnold, Maurice Edgar, Jr.
Arsenault, Charles A.
Brown, E. E.
Burney, William Morrow, Jr.
*Elliott, Charles H.
Flowers, Jack J.
*Fox, Bruce W.
Godell, John J.
Graham, Robert C.
Hadaway, W. R.
Hilton, Richard C.
*Husum, Charles J.
*Koppel, David G.
Mataya, Jack L.
Moore, D. B.
*Morgan, Henry W.
*Ronneberg, Lawry H.
*Thorsen, Wm. G.
Voelker, H. L.
*Wahlers, S. W.

Vernon
*Jechow, Braden W.
#Thompson, Joe A.

Vidor
Stokely, Paul W.
Walker County
Weinzierl, John F.
Waxahachie
Shackelford, Lewis L., Jr.
Wichita Falls
Becker, Clarence Wilbur
Bissett, E. Clark
Bradley, Joe R., Jr.
Crain, R. A.
*Farrow, Mart O.
Gilmore, John A.
Guntharp, John H.
*Harris, Alfred H., Jr.
Harvey, William P.
Jones, Ralph M.
*Kadane, Jack E.
Mayfield, W. I.
Reynolds, E. E.
Travis, Lloyd R., Jr.
Warren, Kenneth A.
Weeth, Chas. A.
Whitney, Vernon E.
Woodville
O'Brien, S. D.
Yoakum
Autrey, D. W.
Farrow, B. D.
Hall, Frederic C.
Love, Perry R.
Pettus, William F.
*Spence, H. C., Jr.

UTAH

Bountiful
*Mabey, Don Russell
Monticello
Smith, Hobart C.
Orem
*Hansen, Don A.
Price
*Basye, Edward R.
*Brown, Roger L., Jr.
Provo
#Campbell, Robert E.
Salt Lake City
*Berg, Joseph W., Jr.
*Blackburn, Harry E.
Brodine, Robert V.
#Cannon, Emerson T.
Cheney, John Robert
#Confer, Howard Lee
Cook, Kenneth L.
*Cottle, Elwood M.
#Dolan, William M.
Eardley, A. J.
*Erwin, John W.
#Evans, Hilton B.
Hobbs, T. E.
*Ivie, Floy L.
#Johnson, John B., Jr.
Lacy, R. J.
#Mandel, Peter, Jr.
*Mardirosian, Azad
Marquardt, Carlton M.
*Morris, Edward W.
#Myers, Richard L.
#Newsom, Donald Richard
Peterson, V. E.
*Trepagnier, Harold J.
Quigley, M. Darwin
*Saegart, William E.
Shannon, Charles W.
#Smith, Paul G.
#Stewart, Samuel W.
*Thiel, Edward C.
Thomas, Robert P.
*Whipple, R. W.
Willis, Howard A.
Wilson, Clyde H.
Wilson, L. M.
Vernal
Josselyn, Walker H.
*Roper, Donald W.

VIRGINIA

Alexandria
*Grolla, R. C.
Moxham, Robert M.
Smitherman, Lynn A.
Arlington
*McConnell, E. B., Jr.
*Moore, L. E.
Prade, Nat H.
Ft. Belvoir
Nelipovich, Daniel J.
Ft. Lee
*Price, Charles E., Jr.
Mineral
Smith, A. R.

WASHINGTON

Fairchild
Bender, Hubert L.
Kennewick
#House, Lewis L.
Mukilteo
*Tait, Jess Thomas
Olympia
*Cooper, Jess F.
Seattle
#Blank, H. Richard, Jr.
*Foster, Robert J.
#Glinkman, Jack V.
Hall, Robert A.
Howell, John L.
West, S. Stewart
*Wolf, Marvin A.
Spokane
Corbin, L. P., Jr.

WEST VIRGINIA

Prince
*Sykes, Robert
Princeton
Straley, H. W., III

WISCONSIN

Black River Falls
*Trask, A. Hugh
Chippewa Falls
*Ostenson, Ned A.
Gile
#Machesky, Lawrence F.
Madison
#Adams, Budd B.
#Behrendt, John C.
#Chapman, Rodger H.
#Haubrich, Richard A., Jr.
*Johnson, Robert W., Jr.
#Mack, John W., Jr.
#Myer, Robert P.
#Rose, John C.
#Weart, Wendell Duane
Woollard, George P.
Oshkosh
#Hinze, William J.

WYOMING

Casper
*Benson, Albert E.
*Blaire, Donald H.
Bone, Robert M.
*Bynum, George R.
*Carter, Norman A.
#Chase, Mrs. Gordon W.
*Critchfield, Ted E.
Dodson, Herbert F.
Earl, John H.
Ellis, George L.
*Erickson, John W.
*Farmer, Wesley N.
Faust, S. R., Jr.
Fenwick, Willis H.
*Ferree, C. M.
Goodwin, Paul E.
*Hampson, Arnold G.
Hawkes, Wendall H.
Heim, Jean W.
*Higgins, Robert L.
Hopkins, James S.
*Huff, James F.
Jennings, Bruce M., Jr.
*Johnson, Richard C.
*Jones, Herbert Gene
Kellogg, Harry L.
*Koch, Barry W.
*Lake, Charles L.
Larguier, Leonard J.
Lechtenberg, W. F., Jr.
Lisco, Richard K.
Ludwick, C. C.
Massey, Roy W.
McGrady, Dupree
McKeever, J. H.
Meade, George N.
*Medlock, Ray
Monhollon, H. T.
Partridge, John F., Jr.
Rader, Miles T., Jr.
Ralph, Pierson M.
*Reed, Laney G.
Roberts, Grant M.
Roberts, Homer E.
Sawyer, Noah G., Jr.
*Schweiger, Charles E.
*Sims, Jesse O.
Spindle, F. D., Jr.
*Wagner, Richard L.
Walczak, Michael J.
*Wells, William E.
*Whitaker, Richard Owen
Winfrey, D. B.
*Woodward, Thomas C.
#Wulf, George R.
Zieve, Robert L.
Cheyenne
#Brown, David L.
Jolliffee, Donald C.
*Kvenvolden, Keith A.
*Yuzbick, R. J.
Zebal, George P.
Cody
*Ashley, Jesse E.
Brooks, W. T.
Douglas
Burnham, Donald E.
*Bursk, Phillip H.
*Dufresne, Daniel A.
Dumas, W. B.
Guernsey
#Seward, Franklin A., Jr.
Lander
*Sodowsky, R. A.
Larmie
Capp, J. T.
*Opland, Homer N.
*Plott, William B.
*Stephens, Ernest, Jr.
Lusk
Stafford, C. J.
Mills
*Brown, C. Milan
Newcastle
*Bernheimer, Fred L.
Martens, Willis P.
Osage
#Thorson, James D.
Rawlins
Benton, Douglas F.
Dallison, Sam James
Johnston, Frank M.
*Kennedy, Howard L.
*Kraye, Robert F.
*Persinger, Richard R.
*Peterson, Wendell E.
Riverton
*Eaton, Fay L., Jr.
*Eitzman, E. T.
Hausladen, A. J.
*Henning, David L.
#Hollingsworth, James C.
Pollet, Arthur
*Smith, David J.
*Sollenberger, John D.
*Tackenberg, Pieter Terry, Paul V.
Rock Springs
Fidlar, M. M.
Gaither, Harold L.
*Tomlin, Walter L., Jr.
Sheridan
*Abbott, William C.
Trostle, Thomas Dale
Thermopolis
*House, H. M.
Torrington
*Roripaugh, Chas. C., Jr.
Wheatland
*Bostick, Paul J.
Worland
*Brown, Jackson W.
*Endacott, Foster E., Jr.
*Horino, Frank George
Jackson, Rodney W.
*Krug, Eugene H.
*Oram, Peter M.
Rupert, James W., Jr.
*Walz, Harry B.
*Wilson, Donald E.
*Younger, Charles Leslie

U. S. POSSESSIONS

ALASKA

Fairbanks
*Diltz, Emory Eakman

HAWAII

Hawaii
*Eaton, Jerry Paul

FOREIGN COUNTRIES

ADEN

Aden
Reyburn, C. K.

ALGERIA

Alger
Beer, Fritz R.
*Dunoyer, Philippe
Kau, Wilhelmus J. C.
Ortynski, H. I.
Van Keulen, Johannes

ARGENTINA

Aguaray
*Fernandez, Gonzalo
Bahia Blanca
Tognon, Juan Francisco
Buenos Aires
Berros, Salvador A.
Binetti, Vincente
Llorden, Juvenal
Munoz, Noble
*Murut, Aldo Raul
Orellana, E. I.
Vila, Fernando
*Voznesenski, Demetrio
Ciudad Eva Peron
*Trejo, Cesar Anselmo
Haedo
Rey, Pedro
Mendoza
*Buttini, Bernardino E.
Rivadavia
Cesanelli, Metello
Rosario (Santa Fe)
*Gurmendi, Juan C.
*Mintzias, Blasis

AUSTRALIA

New South Wales

Canberra
Smellie, Donald W.
Sydney
Marshall, C. E.

Queensland

Brisbane
*Webb, John P.

Victoria

Melbourne
*de Groot, Raymond J. P.
Polak, E. J.
*Smith, Edward Robert
Thyer, Robert F.
Vale, K. R.
Wood, F. W.
Warrandyte
Dooley, J. C.

Western Australia

Nedlands
Weatherburn, K. R.
Perth
Brannian, Ross E.
*Garrett, Maxwell James
Hulsewe, G. J.
Scott, David H.
*Stanley, Donald James
Strutzel, Lewis D.

AUSTRIA

Kantgasse
Schuster, Gerhardt H. W.
Salzburg
Kunz, Bruno F. J.
Schillerstrasse
‡Schubert, Hermann

BELGIUM

Bruxelles
Brognon, G.
Evrard, Pierre

BOLIVIA

La Paz
*Erwin, William M.
Mills, Thomas G.
*Ramirez, Andres B.

BRAZIL

Belem
*Koch, Herman J.
‡Lima, Ibsen Correia
Nery, Raymundo
‡Norem, Nevoy M.
*Rosenquest, John A., Jr.
Stair, Robert Y.
Maceio
Gilbert, Erle W.
Natal
Birge, George J.
*Ducas, J. G.
Mota, Lindonor
Rusch, Peter J.
Rio de Janeiro
Eichelberger, A. M., Jr.
Guedes, Silvio Vilar
Long, James A.
*MacFadyen, Donald A.
Martina, B. A.
Morales, Luis G.
Oddone, D. S.
Portwood, Thomas B. Jr.
*Steacy, John A.
Salvador
‡Bisol, Decio Luiz
Martin, Rodolfo
*Van Der Gracht, William W.
Sao Luiz
*Floyd, Fernando

BRUNEI

Seria
*Murray, Arthur
Romeijn, Cornelis

CANADA

Alberta

Beritley
English, I. J. W.
Calgary
Acheson, C. Harold
Agnew, George C.
Albers, Wilburn F.
Alvey, G. C.
Anderson, W. M.
Armstrong, John A.
*Ashley, Harold A.
*Axford, D. W.
Aydin, M.
*Badgley, Peter C.
Baer, Karl E.
Baillie, Wilfred
Baker, Malcolm E.
Barron, James
Baxter, John C.
Bearden, Carl D.
Beck, August F.
Bediz, Peter I.
Bickel, Harold C.
Bigelow, Donald V.
*Blair, Harrison L.
*Blakely, W. E.
*Blayney, Alan J.
Blundun, George J.
Boulware, Robert A.
Bowden, J. W.
*Bowman, Harold E.
*Brooks, D. G.
Brooks, Robert H.
*Brown, Robert Scott
*Bruce, B. C.
*Buckboro, Kelvie A.
Burns, Jerome L.
Bush, James H.
*Cameron, John B.
Campbell, T. A.
*Cane, Lionel G.
*Carlyle, Robert Harold
Castelli, Lou
Chaney, Ralph D.
Chesher, C. E.
*Chilton, Wm. E.
Christie, Norman J.
Clark, Donald R.
Claus, Spencer
*Clevenger, M. A.
*Comer, Robert L.
Cook, Eugene T.
Coote, George F.
Copeland, R. J.
Cowden, Robert W.
Cox, Harris
D'Arcy, Dale G.
Davis, Rollin E.
Deabler, George
Denton, Eric R.
Desmond, J. M.
Downey, Hugh P.
Dunlap, Albert D.
Ellard, H. Ray
Ellsworth, Frank
*Englebright, William R.
Erickson, E. L.
*Evans, Hugh, Jr.
Farmilo, Alfred W.
Farney, Harold L.
*Farrell, Patrick J.
*Ferrell, George Douglas
Fickinger, Dale E.
*Fjelstul, C. R.
*Frankovitch, C. Jerrold
Freeburg, John J., Jr.
Fuller, John C. J.
*Gaede, John E.
Galeski, Robert B.
Gallacher, John D.
Galloway, John O.
Garrison, Phil H.
Germond, Kenneth W.
*Gibbons, Gervase P.
Gibson, G. G.
*Goldfarb, Lionel J. B.
*Gray, Gordon L.
Green, Thom. H.
*Grimes, Simon L., Jr.
*Grinsfelder, Donald
Haines, E. Greg.
Halbrook, T. A.
Hale, Francis A.
Hale, John D.
Haley, George H.
Hamilton, J. J. S.
Hannon, N. M., Jr.
*Hargrave, Donald R. F.
Hart, Corby L.
*Hassan, Asif U.
*Hatton, William T.
Haun, Glen Robbie
*Heaton, George R.
*Heinrichs, Christian C.
*Herbert, Edward Vernon
Hess, Gordon R.
*Hickey, Francis Lawrence
Hinson, James Milton
Hobson, George D.
Hohag, Walton H., Jr.
Holden, Walter, Jr.
Holland, R. D.
*Holpeany, Franklin E.
*Holtz, Clifford D.
*Horne, David J.
Houghton, H. M.
Hughson, James T.
Ingall, Lindsay N.
Irwin, W. L.
Jacques, Richard D.
*Jensen, Arthur
Johns, N. W.
Johnson, William H.
*Jones, Norman Richard
Junger, Arne
*Kanasewich, Ernest R.
Kaplan, Gerald S.
*Keefe, J. A. C.
Kelcey, M. F.
Kidder, Harold J.
*Knox, William A.
*Kunigiskis, John
*Labicane, T. J.
Lamon, Robert S.
*Lee, Alister A.
Legge, John A., Jr.
Lerm, Gunter
Lipsett, Earl
*Little, J. H.
Lockwood, R. P.
*Loring, Ralph C.
Loven, John W.
*Lundy, Barry R., Jr.
Lytle, Clifford H. B.
*MacAskill, Duncan Donald
*MacDonald, D. A.
*MacGregor, Robert J.
*Mackay, Ian H.
*MacLean, Lachlan
MacMillan, John Kenneth
*MacMillan, Rosemarie
*Mahaffy, Earle F.
Mahannah, R. S.
Maliphant, H. C.
*Manchee, E. B.
*Mann, Horace M.
*Maw, Robert Gordon
*Maxey, William A.
*Mayfield, Ira C., Jr.
*McBeath, Robert G.
*McCaffrey, Richard J.
*McColl, H. Stuart
McConnell, Fredrick Charles
*McCormack, Harold R.
*McDade George Harold
McDougall, Donald B.
McGrew, Harry J.
McKee, Alexander H.
*McKenzie, Miss Hazel Beatrice
McKinnon, F. A.
McKinsey, M. H.
*McNeely, A. Bruce
*Merkley, J. A.
*Merritt, Robert Keith
*Miles, David A.
Miller, Nash H.
Milton, A. A.
Mitchell, Robert O.

Moore, Charles M., Jr.
Moorman, H. R.
Morris, Margaret L.
*Morrison, Trevor W.
*Mouritsen, S. A.
*Moyse, Richard F.
*Moyse, Robert Keith
*Muir, J. R.
Murphy, James B.
Myers, Wm. Howard
O'Bertos, John Johathon
Ogilvie, Wm. P.
Oldaker, Richard B.
Pallister, Alfred Ernest
Patterson, A. R.
Patterson, Samuel O.
Pearson, Harry
Pearson, S. G.
Peterson, K. E.
Phipps, R. T.
*Pierce, Jack M.
*Plotkin, Max
*Poole, Joseph L.
*Pullen, J. R.
Rabey, W. N.
*Reed, Lorne H.
*Reesor, Thomas R.
*Reford, Michael S.
Renden, Hugo R.
*Rettig, Albert Ephel-dred
Richards, L. J.
Richards, T. C.
Rickel, Wesley K.
Rieger, M. J.
*Rimmer, William G.
*Robbins, Vincent L.
*Robertson, Glenn
Robinson, Duncan B.
Robinson, John L., Jr.
Ross, Ralph B.
*Rothenburg, N.
Rozsa, Theodore
Rucker, James H.
Rutledge, E. E.
Sargent, D. M.
Savage, P. J.
*Schlarb, Wm. P.
Schwartz, Bob A.
Seaman, D. R.
*Searcy, Edwin M.
Setters, Jack
Sewell, Francis
Shell, H. E.
*Sherman, G. F.
Siegel, Frank
Skeels, D. C.
*Smith, David W.
Smith, James A.
Smith, J. M.
*Smith, P. N.
Smith, Warren H.
Sosnowski, Jerzy
#Spinney, Robert E.
Sproule, J. C.
*Squire, George D.
Stackler, Phil W. F.
Steel, D. M.
Stephens, Norman R.
Strand, Edwin H.
Swistek, John
*Tessari, John Andrew
*Thomas, Howard E.
*Thomson, Alexander Brian
Tokarski, Stanislaw
*Tompkins, Glen A.
*Treacy, Robert M.
Twardowski, C. B.
Urich, Don L.
Vallat, E. H.
Bekkum, J. J. Van
*Van Der Meulen, H. R.
Van Dijk, A. A. M.
*Viney, Paul E.
*Walker, Donald James
Wallis, F. B.
Ward, John E.
Wegemer, Richard L.
Whitt, Rayburn H.
Williams, Dexter E.
Willner, Carl A.
Wright, James F.
Zarudzki, E. F. K.
Ziegler, James K.
Zimmerly, R. F.

Claresholm
Woker, Leonard A.

Edmonton
*Adams, George W.
Austin, Harold T.
*Boss, F. E.
Coulter, K. C.
*Crane, John D. T.
Crosby, Albert P.
*Dame, A. A.
Daniel, Robert E.
*Danyluk, Harry T.
*Dennis, James N.
Dickson, W. E.
*Garland, G. D.
Gibson, A. S.
Grimes, Joseph Walter
*Hajash, G. M.
Harding, John H.
Hartman, Earl Eldon
*Hill, Norman H.
*Jenkins, Raymond A.
Keller, Ray F.
Kittlitz, Raymond S.
*Kneale, Charles William
*Lipsett, Lloyd R.
*Lishman, John R.
*Morrison, John T.
*Phillips, Alan J.
*Posen, H.
*Procter, John E.
*Root, James R.
Smith, W. Gordon
Sorour, G. L.
Thompson, Andrew A.
*Ustina, Frederick
*Wolikowski, A.
#Wright, Donald E.

Edson
*Stroup, William C., Jr.
*Tarino, Charles A.

Grand Prairie
*McMillan, William R.

High River
*Sample, J. A.

Lethbridge
#Hoffman, Elvin M.
*Mitsunaga, Thomas T.
*Webb, Thomas R. B.

Peace River
*Agnew, Hinds
Armstrong, Archibald C.
*Black, William D.
*Chalus, Walter
Chaput, U. J.
*Dixon, Laurence E.
*Engman, Henry E.
*Harms, William
Hollingshead, Gordon W.
*Houston, T. G.
*Howard, Winston B.
*Hryhor, William
*Hudson, J. A.
*Lee, Loring O.
*Pelzer, E. E.
Schultis, Geo. E.
Stephens, J. L.
*Weisser, Gordon H.

Pincher Creek
*Kilback, Norman R.

Ponoka
*Kennedy, A.
*Spence, Allan K.

Red Deer
Blair, Wm.
*Clark, Earl
*Clements, Wallace E. R.

Stettler
Flower, Louis G.

Winterburn
*Rubenok, Robert R.

British Columbia

Dawson Creek
#Ganguli, Debkumar

Kamloops
*Nelson, Walter I.

Vancouver
Adler, L.
Clark, Arthur Roy

Manitoba

Brandon
*Jones, E. A. W.
*Kaarsberg, E. A.
Robertson, W. A.
*Surjik, David L.
*Wachnow, Wilfred L.

Steinbach
*Goossen, Harvey S.

Winnipeg
*Bergman, L. H.
*McKay, Donald A.

New Brunswick

Bathurst
*Mousuf, Abul Khair

Nova Scotia

Truro
Blanchard, J. E.

Ontario

Chalk River
Keys, David A.

Chatham
*Newton, A. C.

Copper Cliff
*Dowsett, John S.
*Taylor, Ronald R.

Kingston
*Fitzpatrick, Michael

London
*Uffen, Robert J.

Manotick
*Morley, L. W.

Ottawa
Beals, Carlyle S.
Collett, Leonard S.

Scarborough
*Harvey, Herbert A.

Toronto
*Betz, J. E.
Britton, John W.
Cartier, W. O.
*Clifton, Frank
#Faessler, Walter C.
Gilchrist, Lachlan
#Gledhill, Thomas R.
*Hudson, J. Drew
*Johnson, A. E.
Johnson, G. R.
Keevil, N. B.
Lundberg, Hans
Mackay, Douglas Griffiths
McCamus, F. W.
*Paterson, Norman
*Pemberton, R. H.
*Ratcliffe, John H.
Salt, Donald J.
Sander, George W.
Seigel, Harold O.
#Smith, Clark H.
#Sutherland, Don B.
*Thomson, Ker C.
*Ward, S. H.
Westrick, Edmond W.
Wilson, John Tuzo

Weston
Wagg, Donald Maxwell

Quebec

Bourlamaque
Brossard, Leo

Buckingham
Stephenson, Russell W.

Chilougamau
*Predergast, Joseph B.

Montreal
#Gaffney, Terence Joseph
Kaufman, Hyman
*Larochelle, Andre
Middleton, Brian M.

Novarda
*Winkler, Hartmut
Koulomzine, Th.

Saskatchewan

Estevan
*Jackson, Ernest J.

Meifort
*Murchison, J. M.

Moose Saw
Gilliam, James T.

Nether Hill
*Smidt, Jacob W.

Ponteix
*Wright, W. J.

Regina
Bradford, M. D.
Carter, Roland H.
Dalik, C. E.
*Finlay, James C.
Hafer, James A.
*Hayes, James O.
*Hutney, C. P.
Luhrs, Lawrence B.
*McCormack, William J.
McGee, N. W., Jr.
*McIvor, Donald K.
*Miller, Ernest G.
*Mulhall, M. A. E.
Pallat, Rolf E.
*Post, Calvin
*Sawatzky, Henry B.
Stoneman, H. W.
*Terada, Naga R.
Tims, Henry C.
Toland, David R.
*Watson, Bruce Earl
*Wedin, C. R.

Rosetown
*Wiber, John R.

Saskatoon
*Angus, W. R.
*Kreibom, Ernst K.
*Linke, William A.
Rosser, B. A.
#Scheidt, Rolf W.

Swift Current
*Creasey, Ernest W.
*Randall, Peter M.
*Schleinich, John F.

Uranium City
*Walter, John P.

CHILE

Punta Arenas
Breffitt, E. W.
Francis, George F.
Hernandez, R. A.
Laval, Ramon A.
Portugal, Ramon A.
Schneider, Oscar R.

COLOMBIA

Bogota
Chapman, William M.
Duncan, James P.
*Hays, H. Charles
Imle, Harry R.
*Milliken, Robert L.
*Moulton, Frank R.
Nash, Ira L.
Olson, Glen E.
Perry, Charles C.
Scott, C. B.
Spalding, Carlton T.
*Stanley, P. John
*Thielan, Benjamin J.
Thompson, Arthur V.
Medellin
*Allenby, Richard J.
Albright, E. Glenn
Oyapel
Price, Justus V.

CUBA

Camaguey
*Jackson, Wayne H.
Ciego de Avila
*Greene, Thomas R.
Havana
Bornemisza, Stephan Thyssen
Vanderbeek, James Wilson

DENMARK

Copenhagen
Lundbak, Asger N.

EGYPT

Alexandria
Dennis, G. W.
Green, William W.
Guirguis, William M.
King, Laurence K.
*Runte, F. C.
*Russell, Willie Lee, Jr.
Shepherd, C. K.
Strong, J. Randolph, Jr.
Cairo
Barkouky, Ahmed Nasr El
Bixby, Robert H.
Eicher, Donald B.
*Saint, Rene
Stoutjesdyk, P. S.
*Wafick, Mohammed

ENGLAND

Glam
*Rees, J. C.
Holwood-Keston
*Anstey, Nigel A.
Bourne, I. C. J.
Brummitt, J. G.
*Campbell, Francis J.
Christie, Donald F.
Dod, G. F.
Edwards, Thomas Ellis
Fitch, A. A.
Graf, Victor V.
Hartley, D. A.
*Haskett, R. W.
*Heads, J.
*Jenyon, M. K.
*Lazenby, P. G.
*Lee, Maurice Leonard
Lindsey, E. B.
*Marshall, John K.
*McPhee, William S.
*Narayana, J. V. S.
O'Brien, Terence
Packer, Albert George
Pezarro, Theodore A.
*Priddle, D. E.
Smith, J. K.
Van Der Linden, E. J. P.
Van Der Linden, E. P. E., Jr.
*Williams, Hugh W.
*Young, Wm. M.
Liverpool
*Wilson, C. D. V.
London
Brown, Donald R.
Brown, F. W.
Colley, G. C.
Davies, Richard
George, W. J.
Germain-Jones, D. T.
*Hodges, William George Hamer
Jewell, F.
Makowiecki, L. Z.
Malone, Adam B.
*Parry G.
*Randell, John T., Jr.
Robertshaw, J.
Wyrobek, S. M.
Manchester
*Roberts, B. C.
Mordon, Surrey
Dundon, Robert F.
Newcastle-on-Tyne
Jackson, J. B.
North Wales
Jones, John H.
Notts
Lamont, A.
O'Brien, Peter N. C.
*Winstanley, Oliver B.
Middlesex
*Domzalski, W.
*Ley, J. R.
St. Albans
Tait, George
Surrey
Tarrant, L. H.
Winchester
*Bennett, Geoffrey L.

FINLAND

Abo
Metzger, Adolf A. T.

FRANCE

Begles
Brewer, Herbert L.
Farando, A. J.
*Keeler, John W.
*Nichol, Frederick D.
Thompson, Jay F.
Bergerac
*Dekker, Dirk
Chatou
*Mainguy, Maurice
Montrouge
Lemasne, G.
Paris
Aubert, J. E.
Aynard, Claude
Baboin, Guy E.
Baranov, Vladimir
Beaufort, Lucien
Blondy, F. H.
Bouchon, Rene Philippe
Breusse, J. J.
Cagniard, L.
Desaint, R. H.
Donner, M.
Geneslay, Raymond Henri Joseph
Giraud, Paul
Goguel, Jean
Henquet, R.
*Houbas, Robert
Huot, G.
Kunetz, Gesa
Leblanc, Jacques
Saget, Andre Le
Maillet, Raymond J.
Mathieu, Jean Leon
Mathiez, Jean Paul
*Migaux, Leon
Neumann, Robert
Pieuchot, M.
Ratliff, Guy M.
Richard, Henri
Roger, A. H.
*Royer, G.
*Saint-Legar, Yves
Seydoux, A. E. R.
Sundt, Olaf F.
Pau
Beique, Louis
*Descher, Anton H.
Schoeffler, Jacques
Weatherby, S. Preston
Rueil-Malmaison
Mouche, Theodore J.
Seineet Oise
*Bradley, Francis T. H.
Delflache, A. P.
*Schwing, Edwara H., Jr.
St. Cloud
Allen, Samuel J.
*Gilland, William T.
Strasbourg
Grepin, Andre'

GERMANY

Barkhovenalle
##Mintrop, L.
Bonn
Rosenbach, Otto
Hannover
Brinckmeier, George
Gees, R. H.
Heimburg, Fritz
Krey, Theador C.
Maass, Hans Wilhelm
Schulze, Gustav-Adolf
von Helms, Hans
Zettel, Waldemar
Ludwig
Schleusener, Alfred
Sachsen
Kaselitz, Fritz

GOLD COAST

Accra
Dresbach, C. H.
Alger
*Cholet, Jacques
Johannesburg
Fletcher, H.

GUATEMALA

Guatemala City
*Seidner, Edmond

HONG KONG

Hong Kong
Fu, C. Y.

ICELAND

Reykjavik
Bodvarsson, Gunnar

INDIA

Bombay
*Deutsch, Ernst R.
Calcutta
Caan, A. J. Z.
Craig, Robert L.
Madhwa, K. R. Simha
Murray, Matthew T.
Negi, B. S.
Rao M. B. Ramachandra
Rao, Suryanarayana M. M.
*Rosen, Ernest W.
Sengupta, S. N.
White, Rex H.
Kharagpur
Bhattacharya, Prabhat Kumar
*Roy, Amalenut
Poona
Banerjee, Santi Lal
Upper Assam
*Awasthi, Anand Mohan
Waltair
*Rao, V. Bhaskara

INDONESIA

Badjubang
Spinks, John
Djakarta
Harding, R. N.
Pakanbaru
*Deibert, Donald H.
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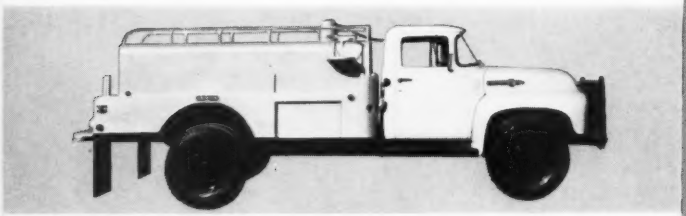

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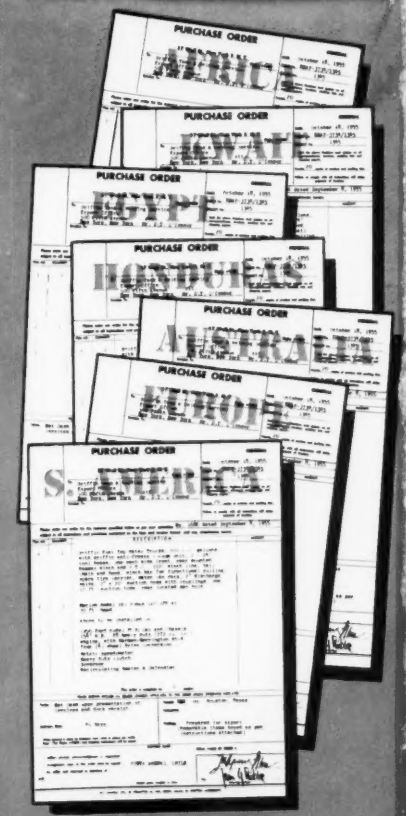

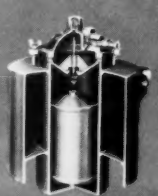

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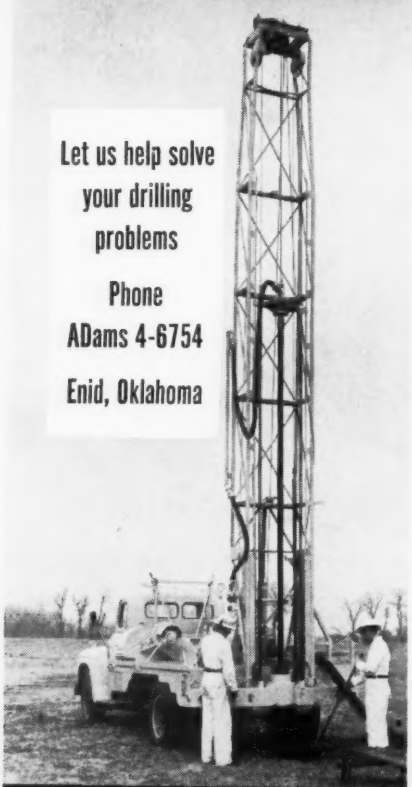

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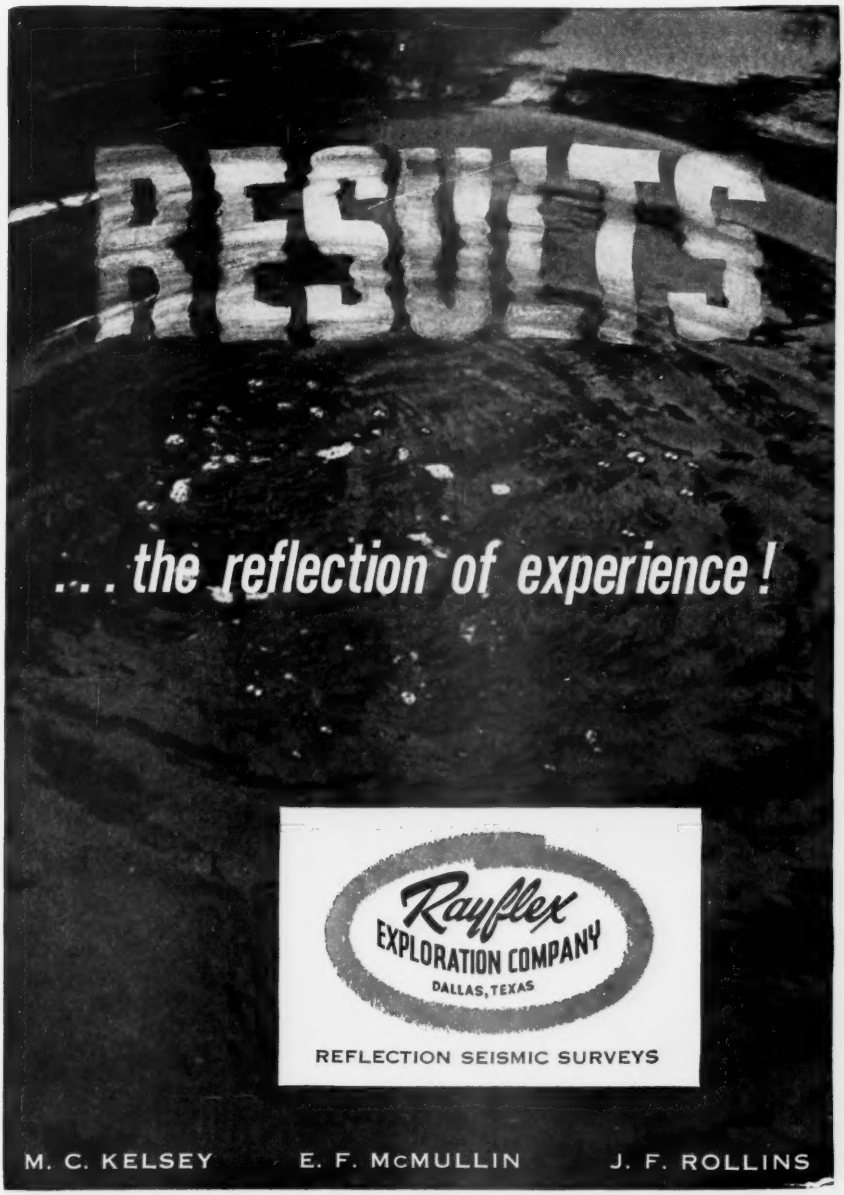
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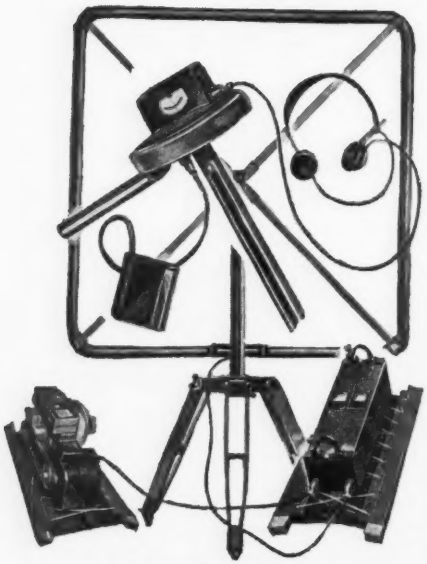

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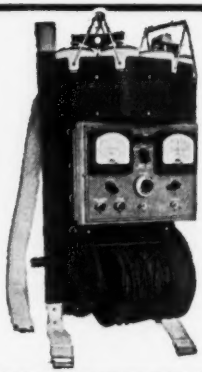

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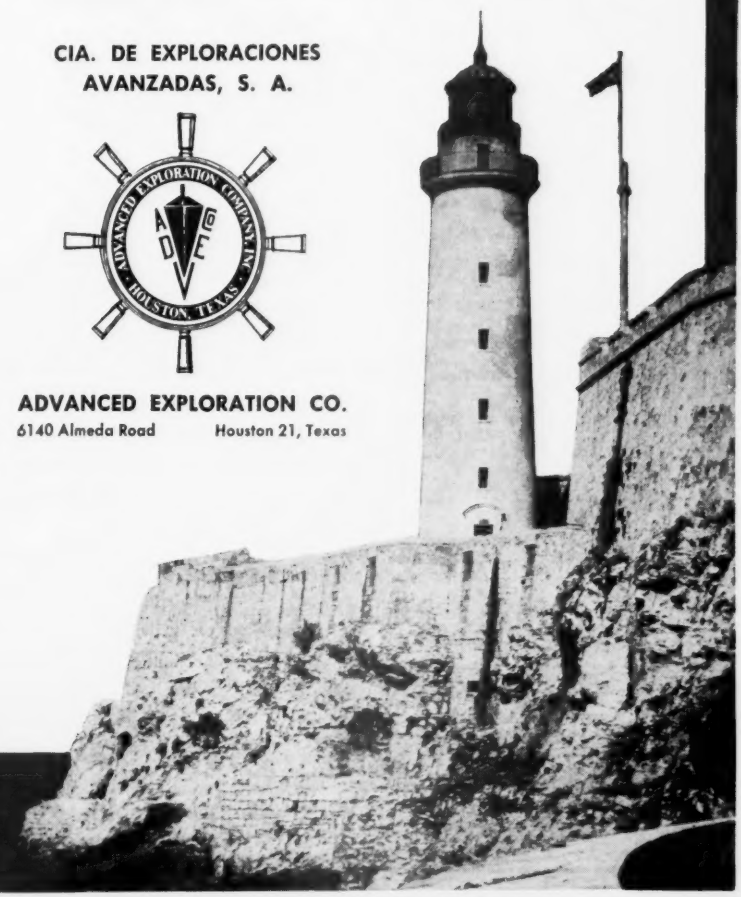

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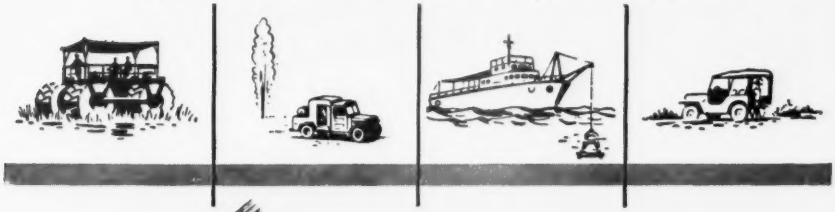

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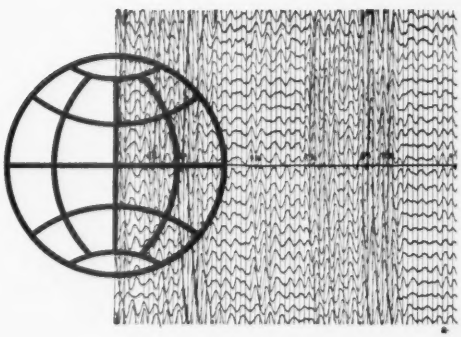

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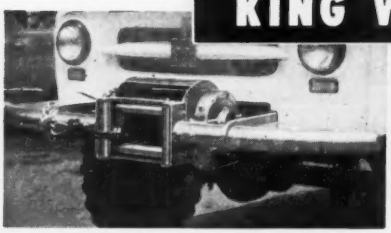

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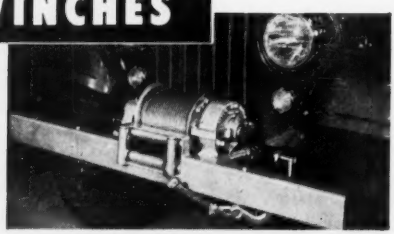

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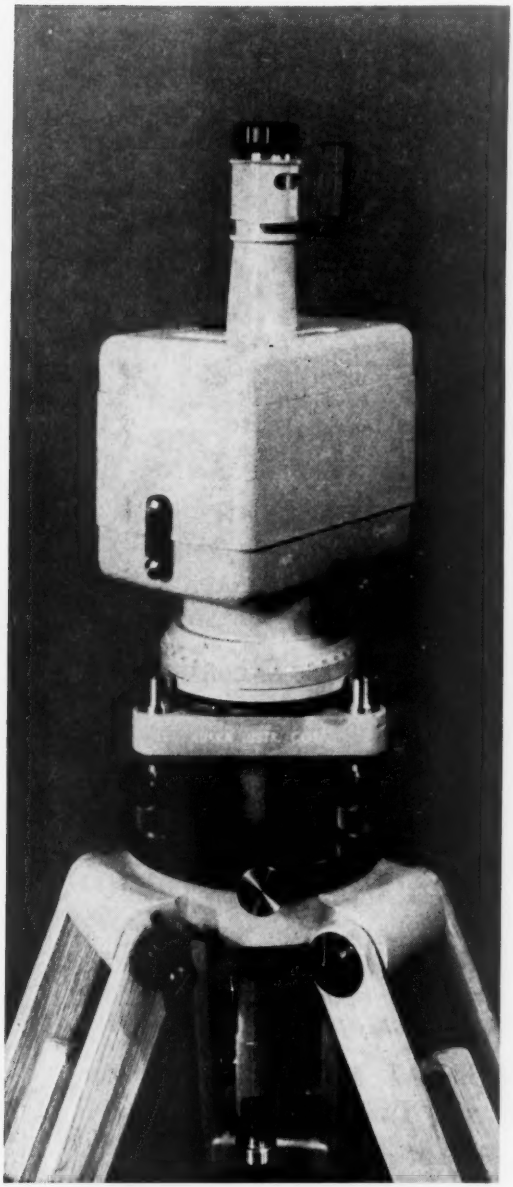

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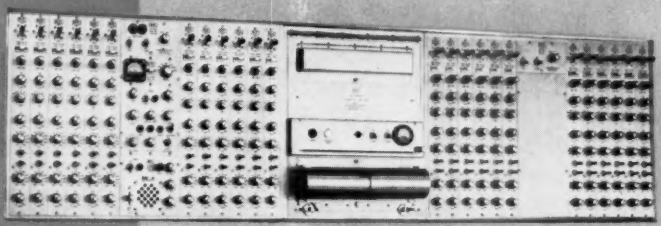

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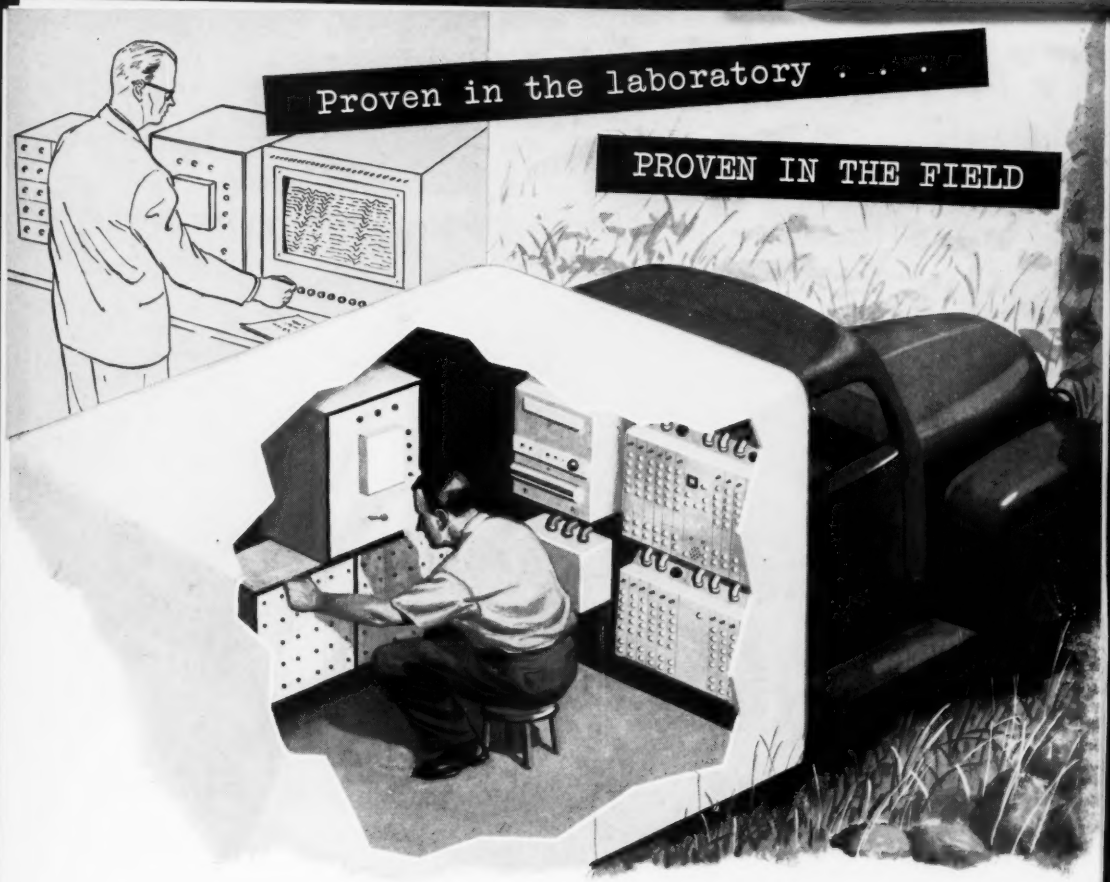

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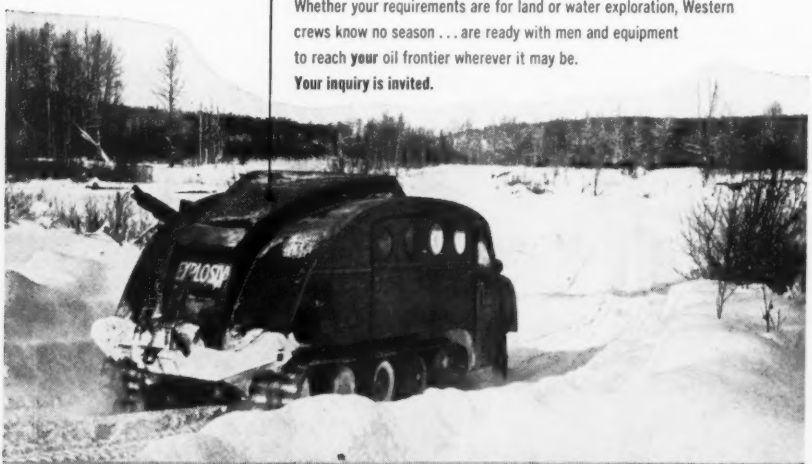

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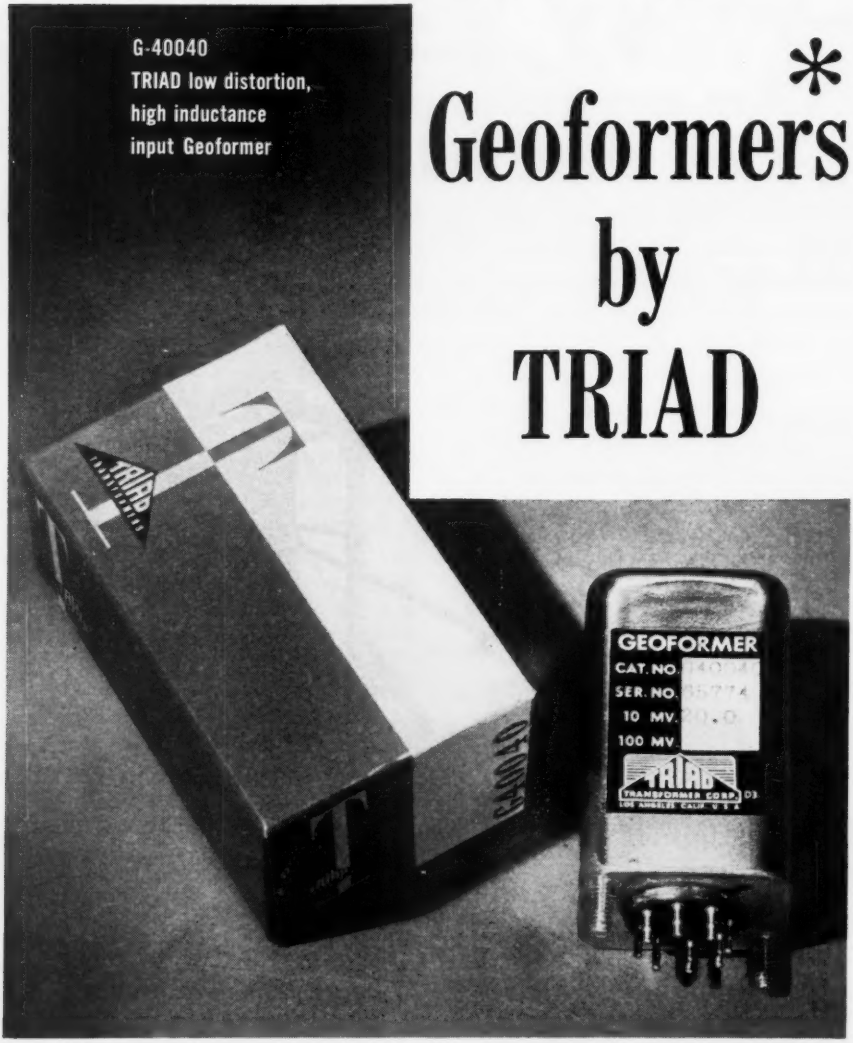

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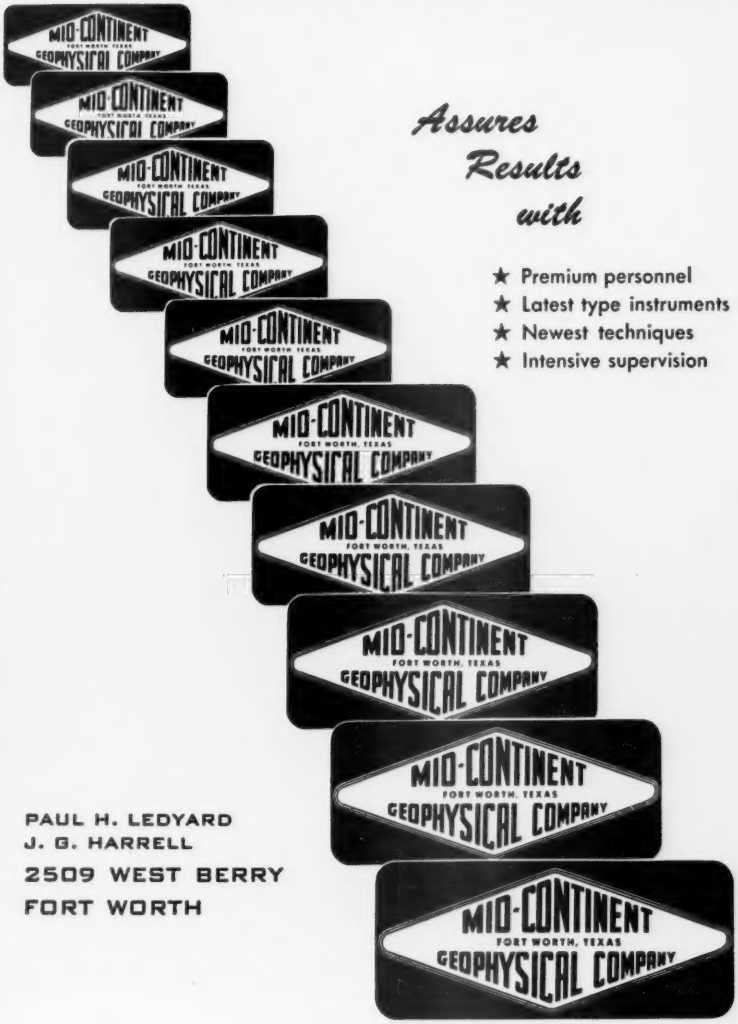

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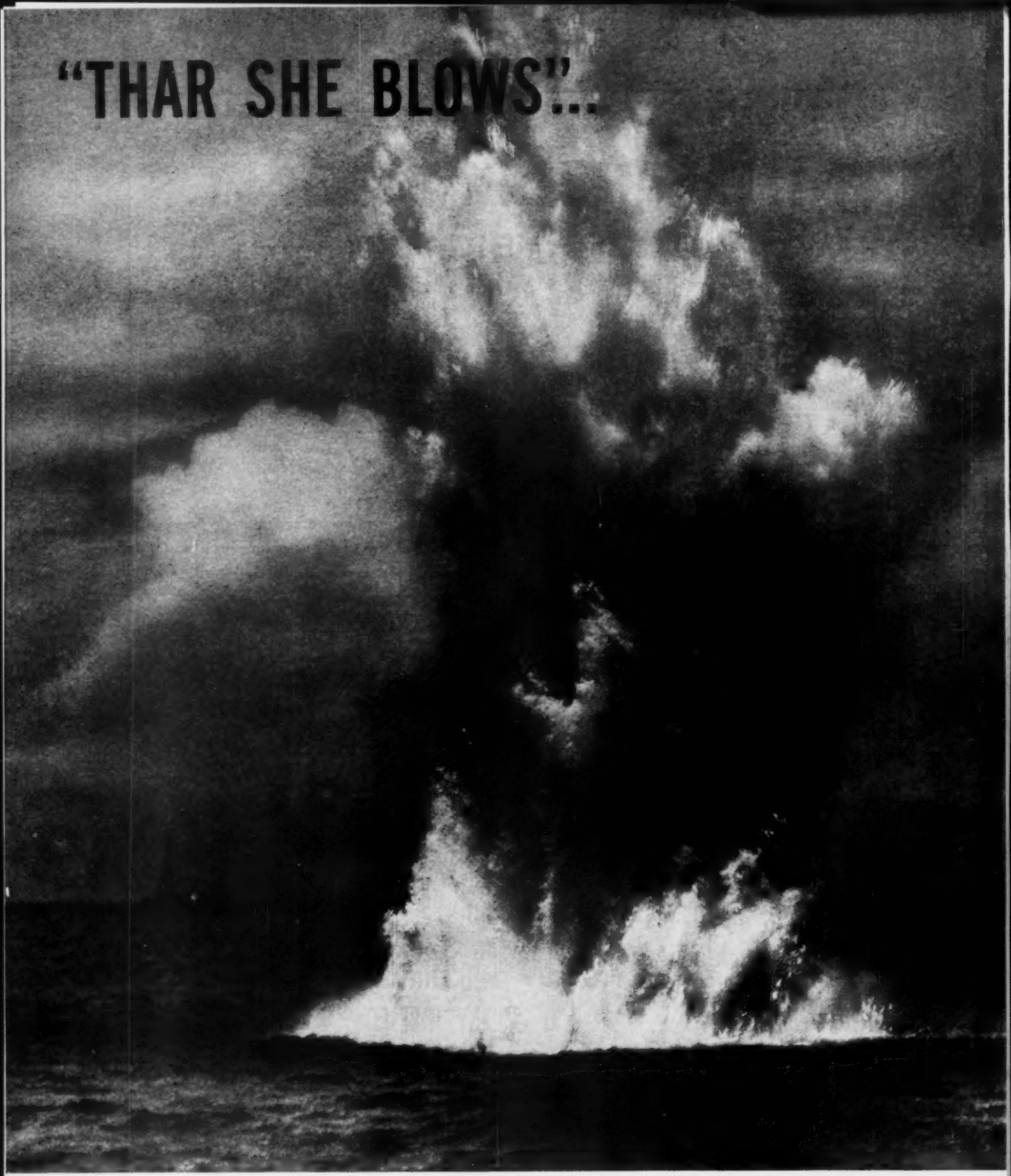

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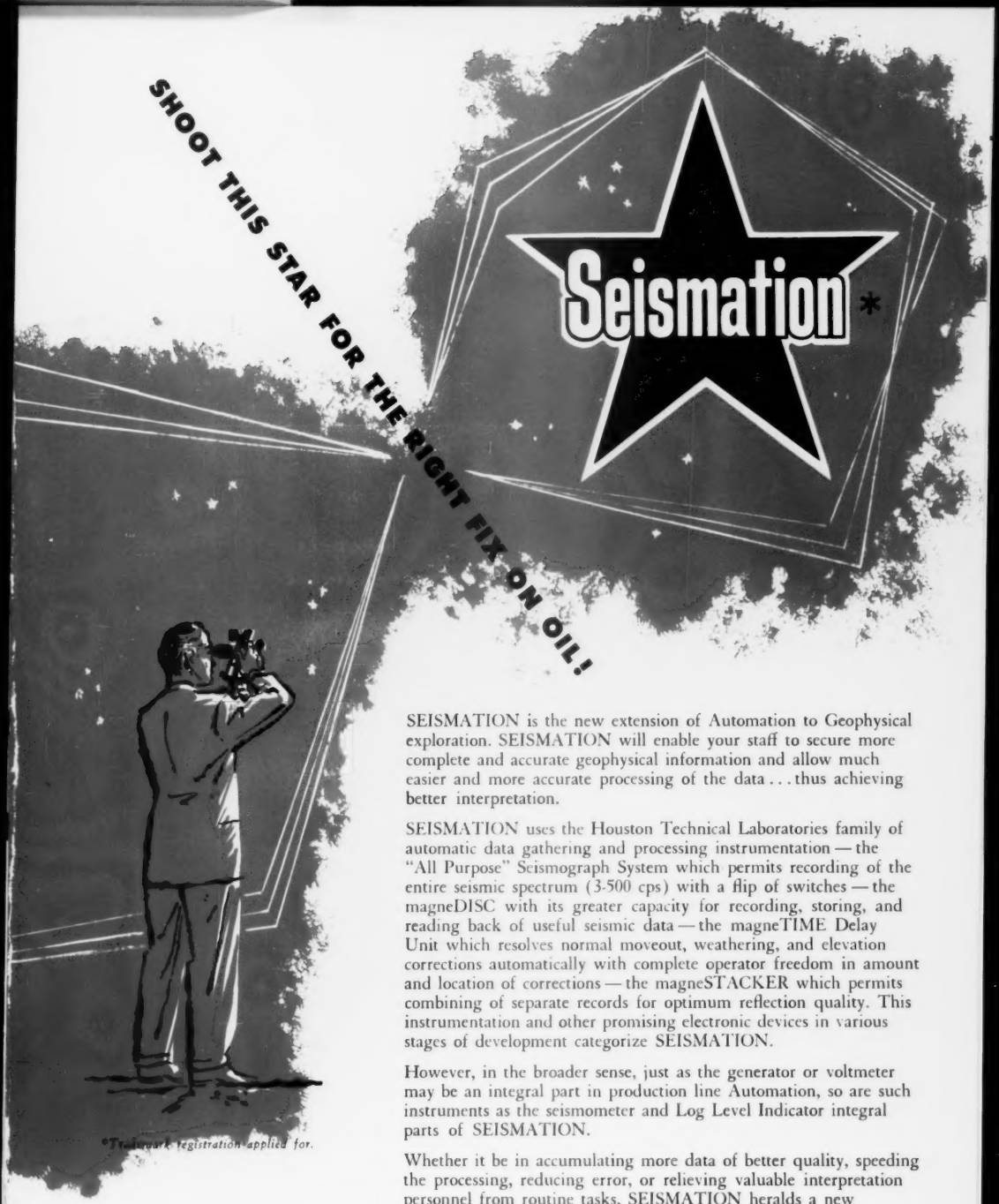

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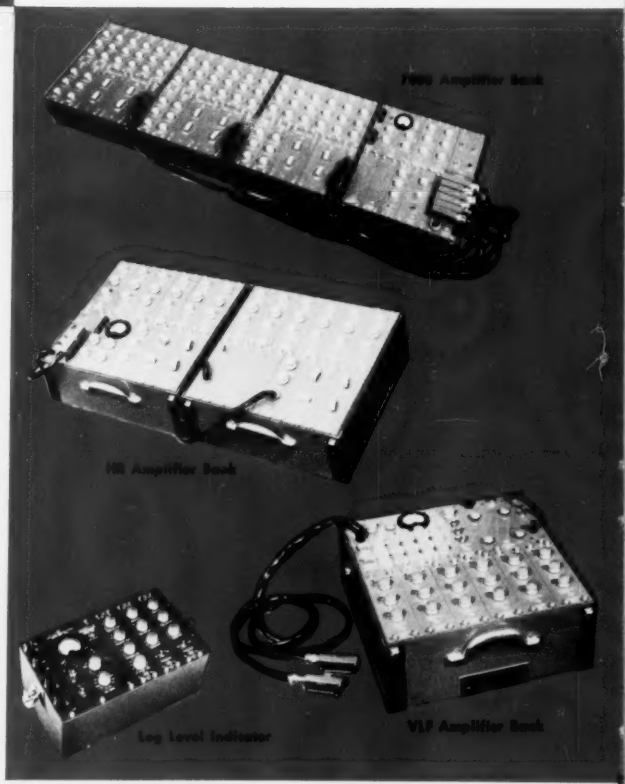

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Transducer Unit showing the recording heads and pressure plates. Other units in the system are the Electronics Case and Power Supply.

Please write for complete information including HTL's special lease-purchase plan on the magneDISC. Specify Bulletin No. S-207.

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1. **Greater Capacity** — 100 data channels, with flexible trace pattern combinations, plus 12 programming channels.
2. **No Drop Outs or Timing Error** due to plastic ripple, plastic discs are thicker than other mediums.
3. **Greatly increased recording head life** due to larger area of contact.
4. **No Discontinuity** — Continuous medium permits either synchronized or unsynchronized shot.
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6. **Can be readily adapted** for sequential recording.
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HTL S-39 dualDAMP seismometer

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The S-39 dualDAMP seismometer employs both electromagnetic and fluid damping, utilizing the advantages of each. The dualDAMP has negligible spurious response, with high lateral stability up to 500 cps.

*$10.00 in U. S. A., Canada, and Mexico . . . outside these countries, $11.00. All prices FOB Houston.

SPECIFICATIONS

Weight	11 oz. (with cap and spike)
Height	1⅞ inches
Diameter	1½ inches
Natural Frequency	13, 17, 20 cps optional
Coil Resistance	500 ohms
Internal resistor for 0.55 critical damping.	390 ohms (20 cps) 470 ohms (17 cps) 620 ohms (13 cps)

Write for Bulletin No. S-310

HTL S-36 and S-36 U VLF Detectors

The S-36 Very Low Frequency detector is greatly responsible for the excellent results, and dynamite economy, now possible in refraction surveys.

The S-36 detector has a relatively large output, 5 volts/inch/second, and its undamped resonant frequency is 2.00 ± .05 cps. Note the difference between the S-36 and S-36 U under specifications.

SPECIFICATIONS

S-36 Detector

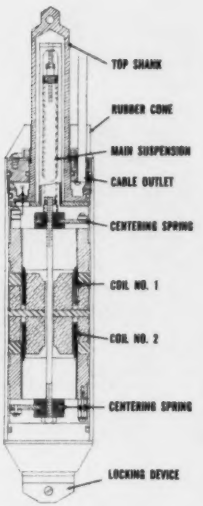
Weight	17 pounds
Height	17 inches
Diameter	3 inches
Natural Frequency	2 cps
Coil Resistance	4000 ohms
Internal Resistor	15 K

(Requires 10-K External Resistor for damping .5 critical)

S-36 U Detector

Coil Resistance	100 ohms
Damping Resistor	150 ohms

Write for Bulletin No. S-312



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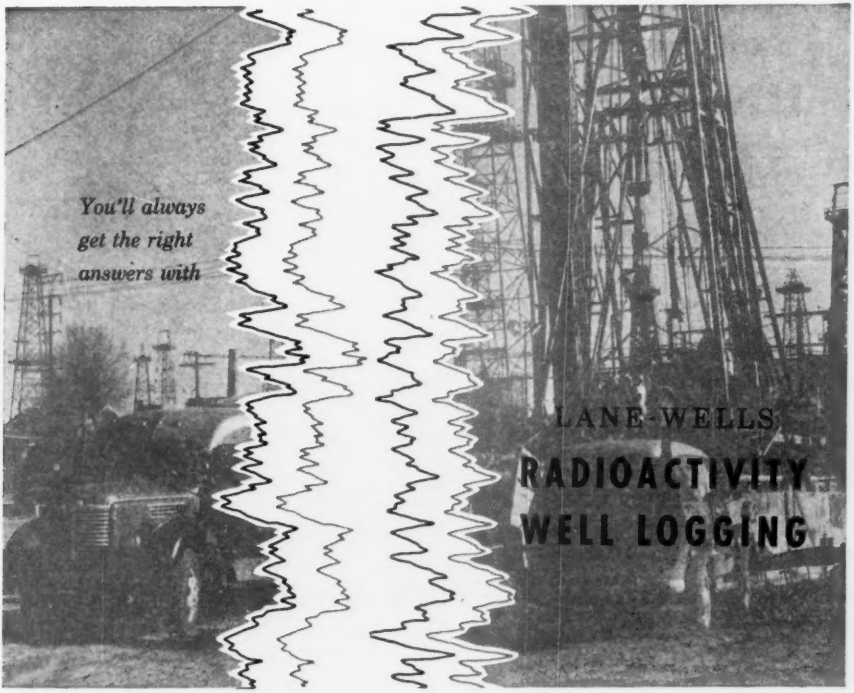

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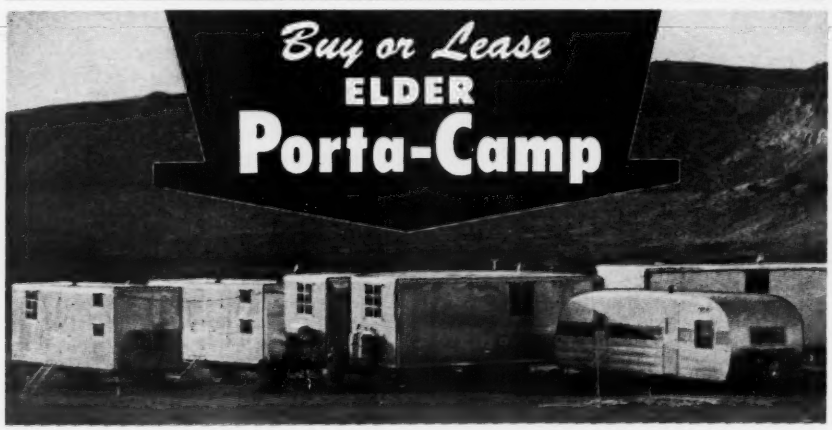

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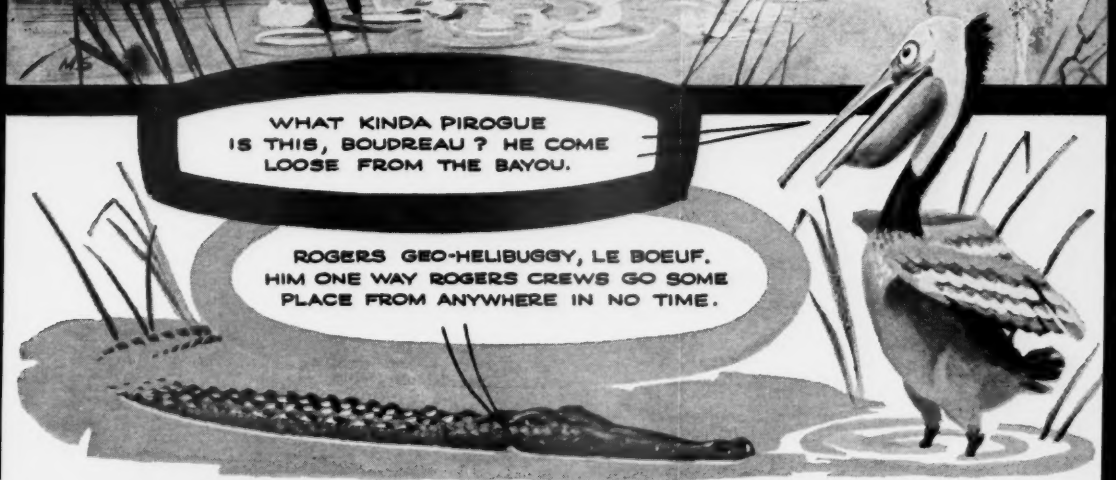
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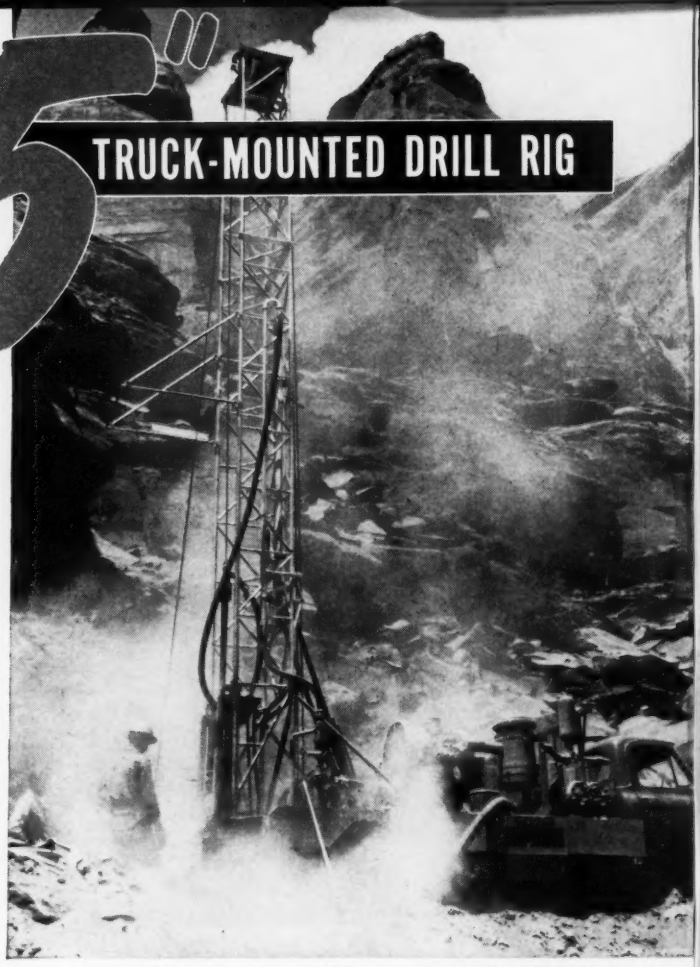

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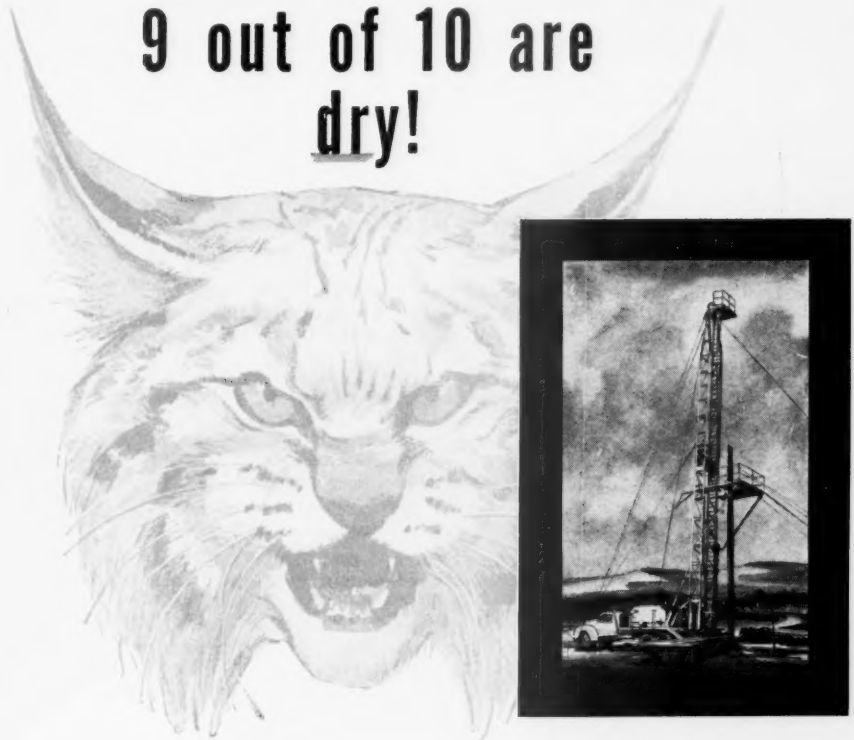

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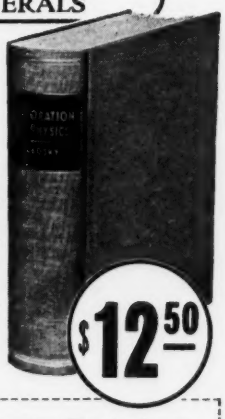

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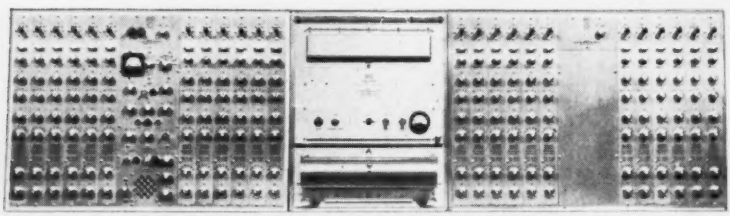

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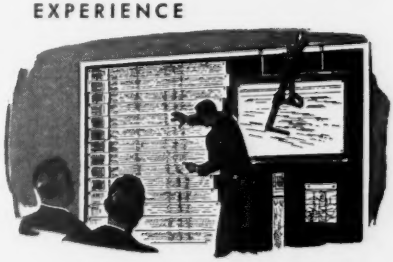

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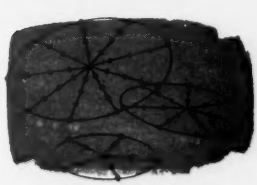

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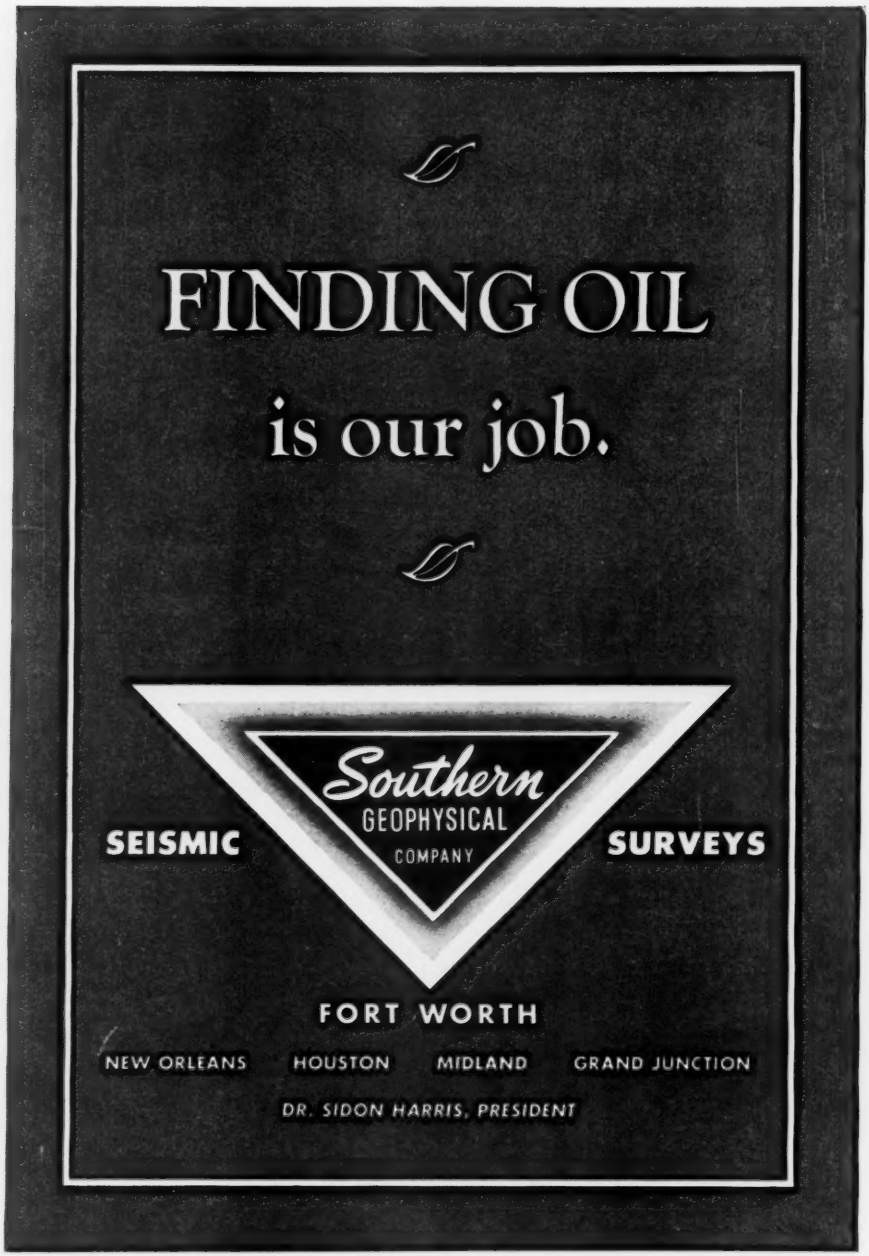
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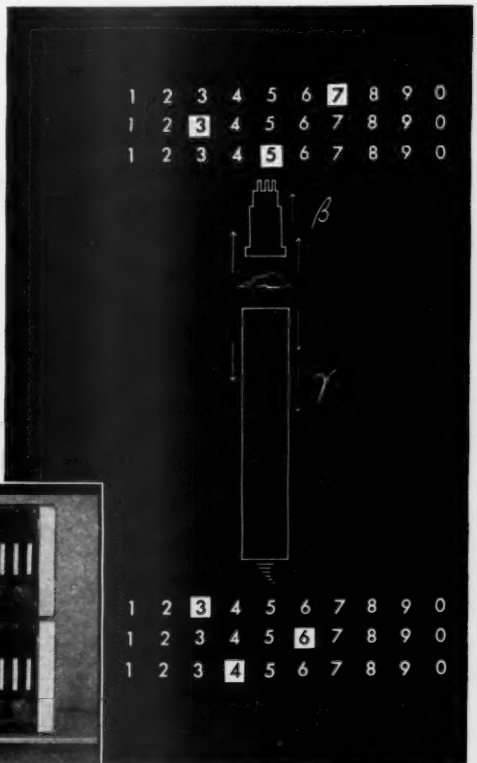

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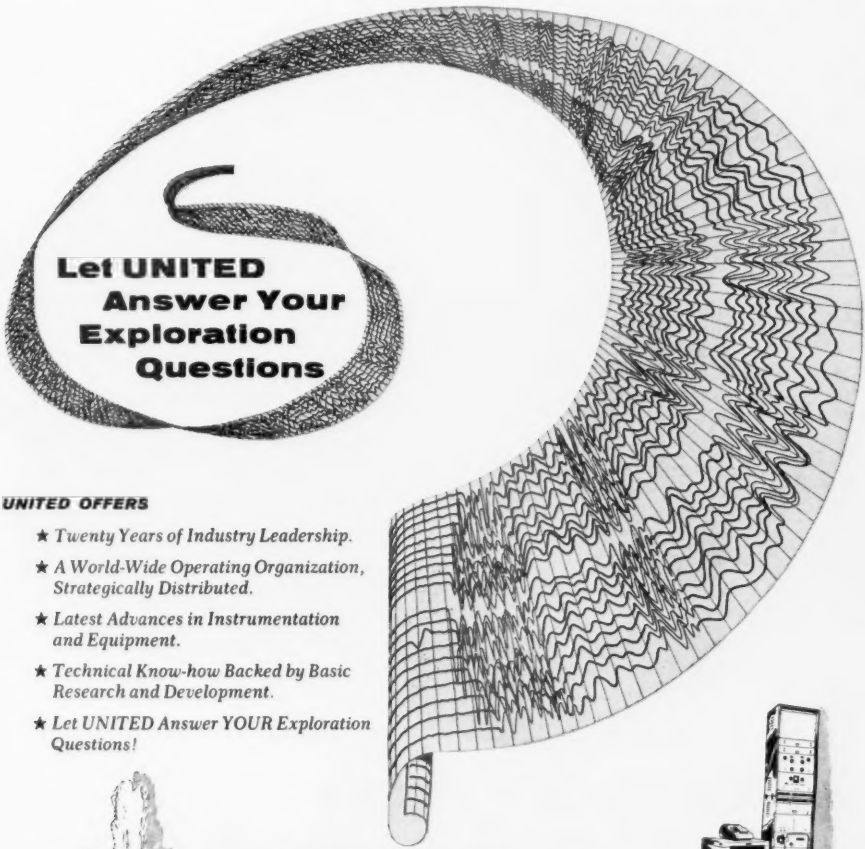

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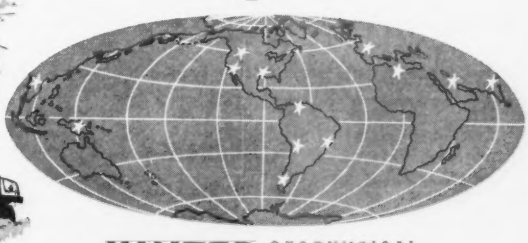

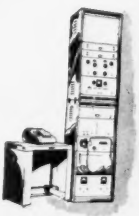

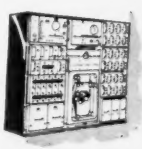

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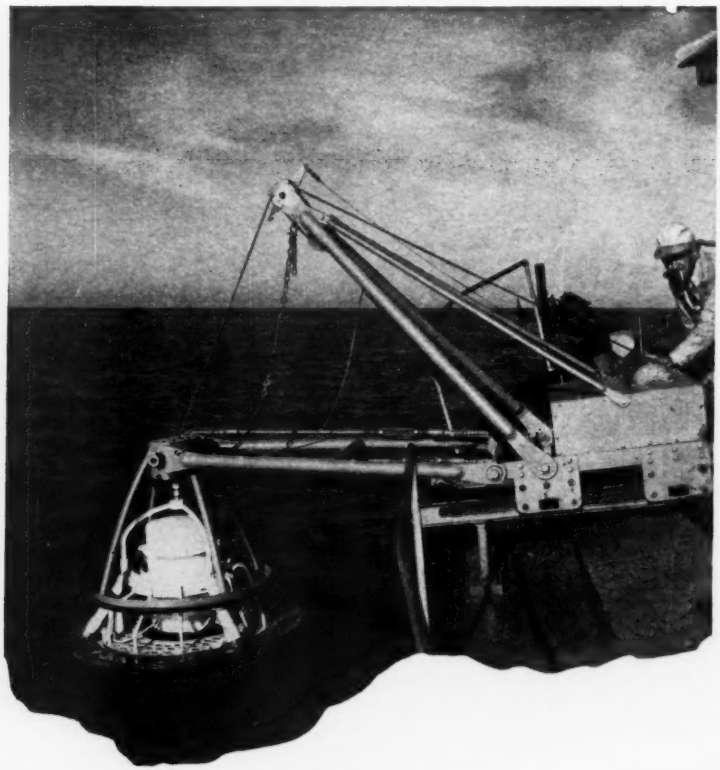

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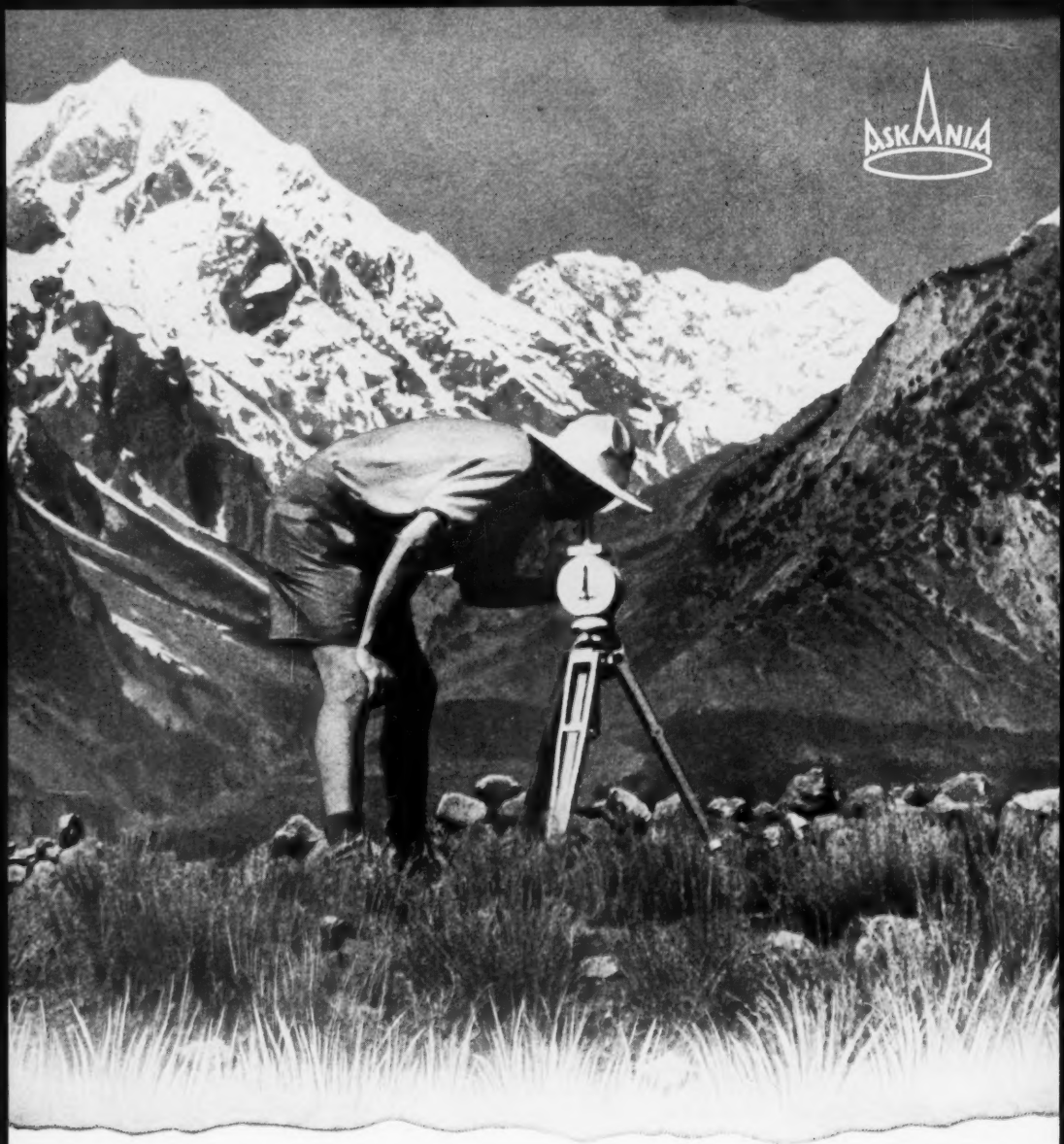

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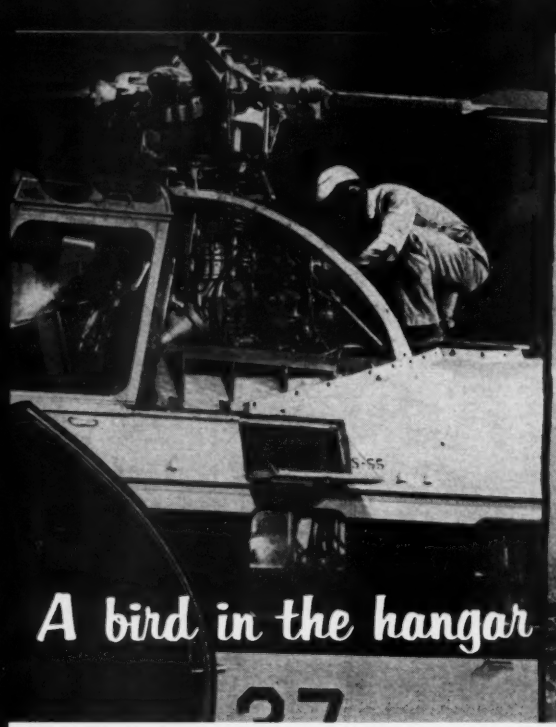

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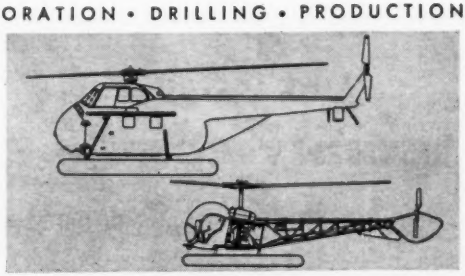

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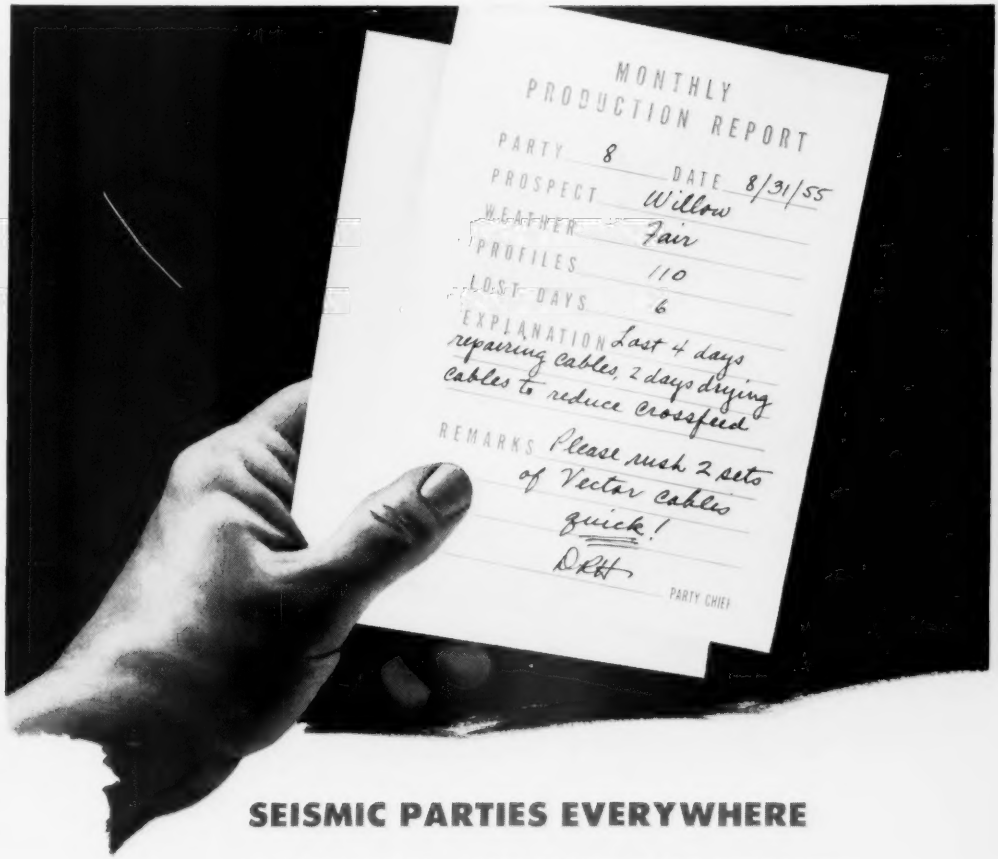

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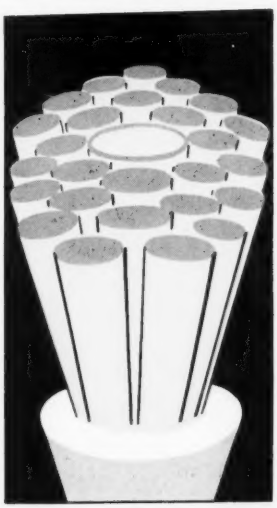

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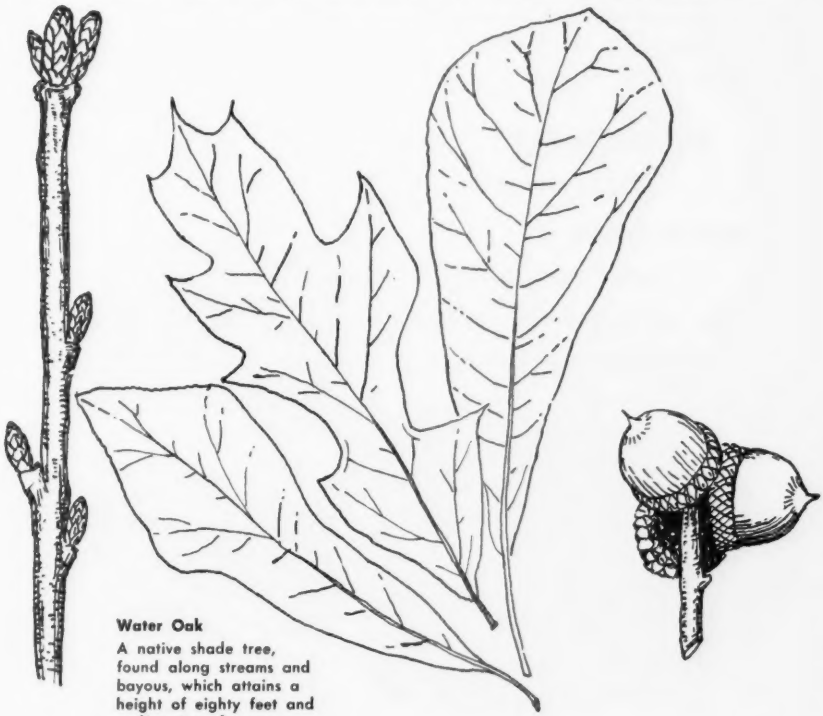

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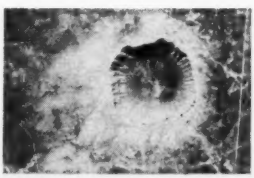

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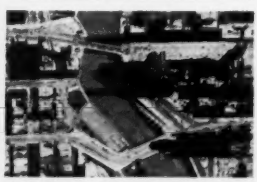

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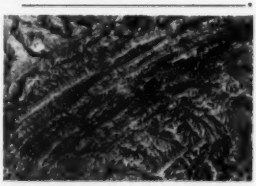

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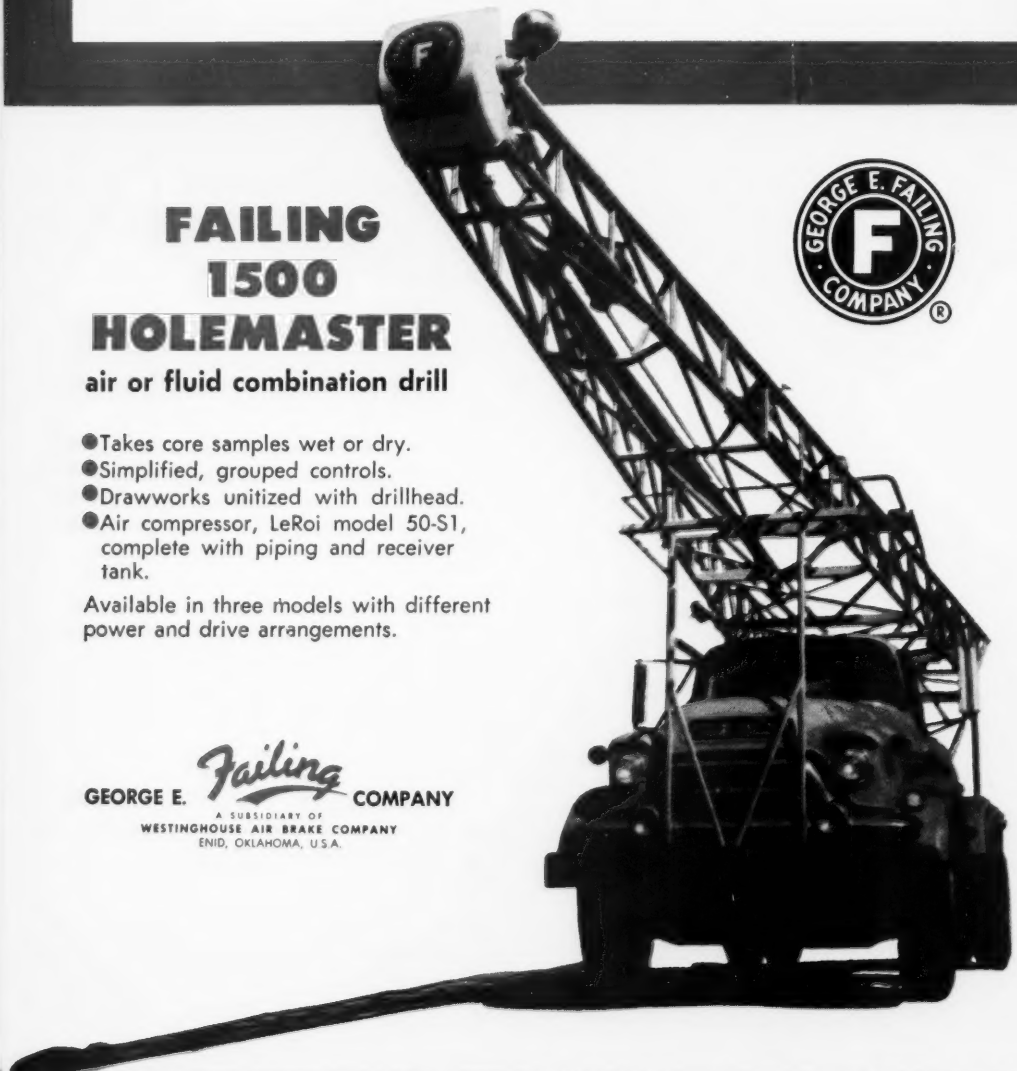

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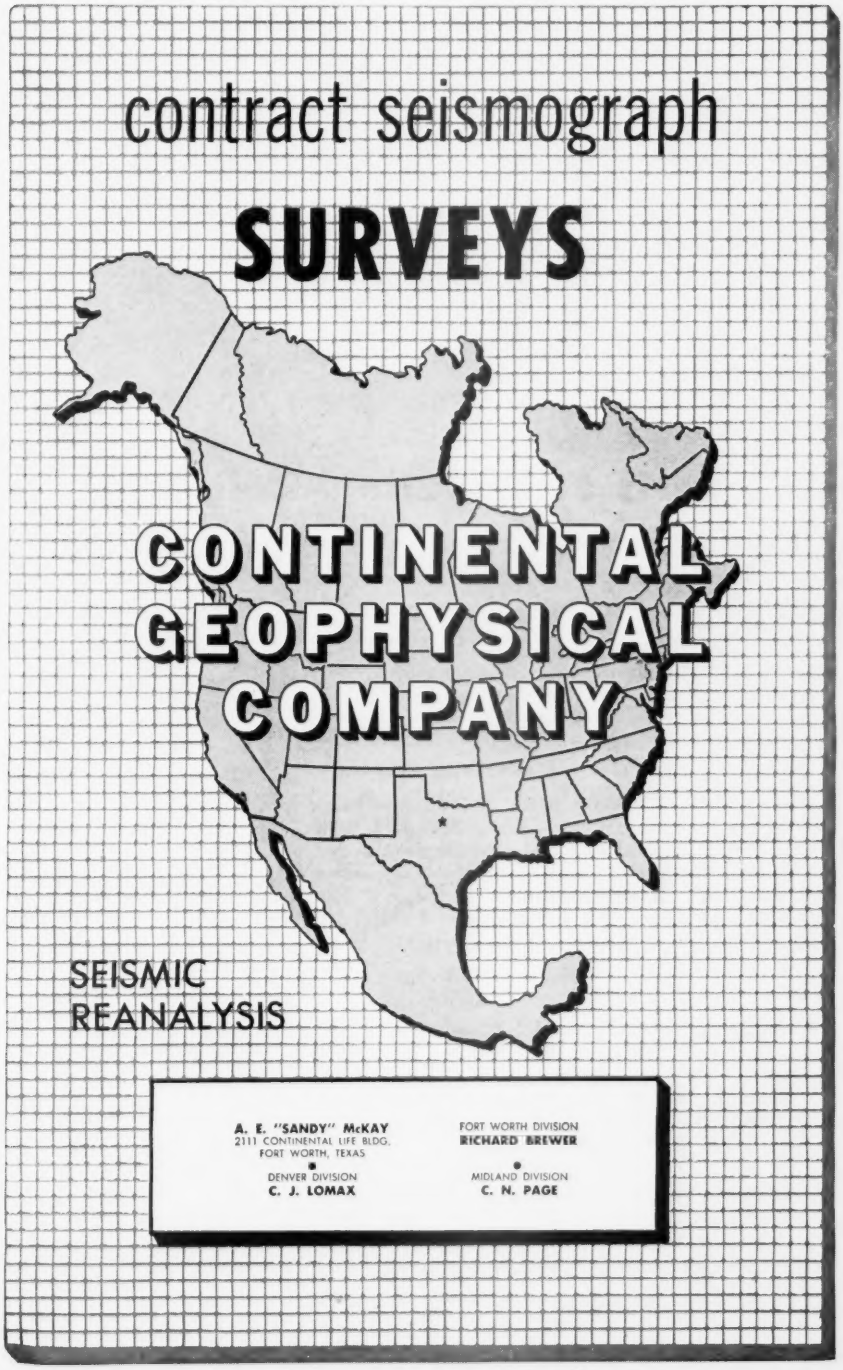

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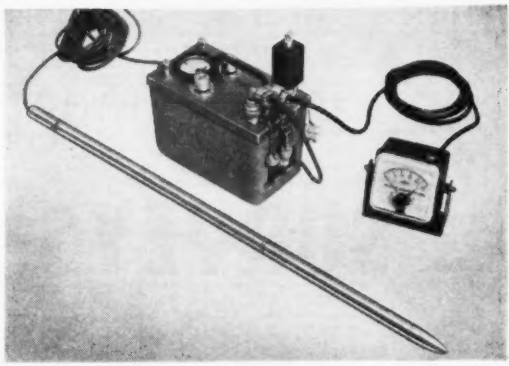

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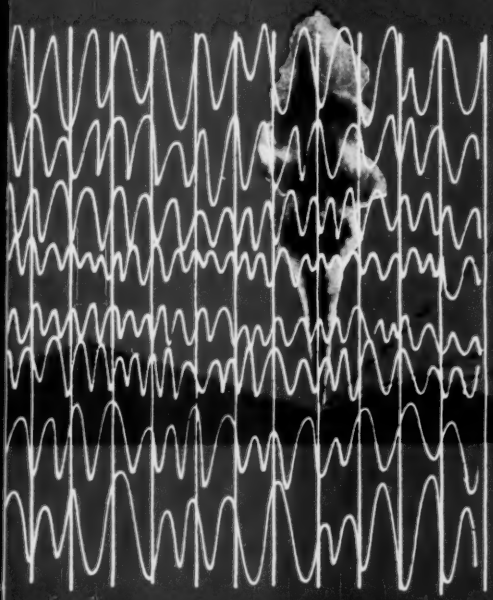
In Canada: Wallace & Tiernan, Ltd., Toronto

A-107

ADC

SUB-MINIATURIZED

TRANSFORMERS AND CHOKES



SAVE VALUABLE SPACE IN COMPACT EQUIPMENT!

RUGGED
Hermetically Sealed

TINY
Only ¾" x 15/16" x 1⅜"

WEIGHT:
Approximately 1.8 Oz.

AVAILABLE IN:
Steel or Mu-Metal Cases

Rigid size restrictions necessary in the manufacture of compact equipment make sub-miniaturized components increasingly important to electronic equipment manufacturers. Measuring only ¾" x 15/16" x 1⅜", ADC's new line of hermetically sealed transformers and chokes save valuable space and have performance ratings equal to or exceeding units of a far larger size. Designed for the geophysical field, modifications of these power-packed units are finding ready acceptance in transistor and other sub-miniaturized circuitry.

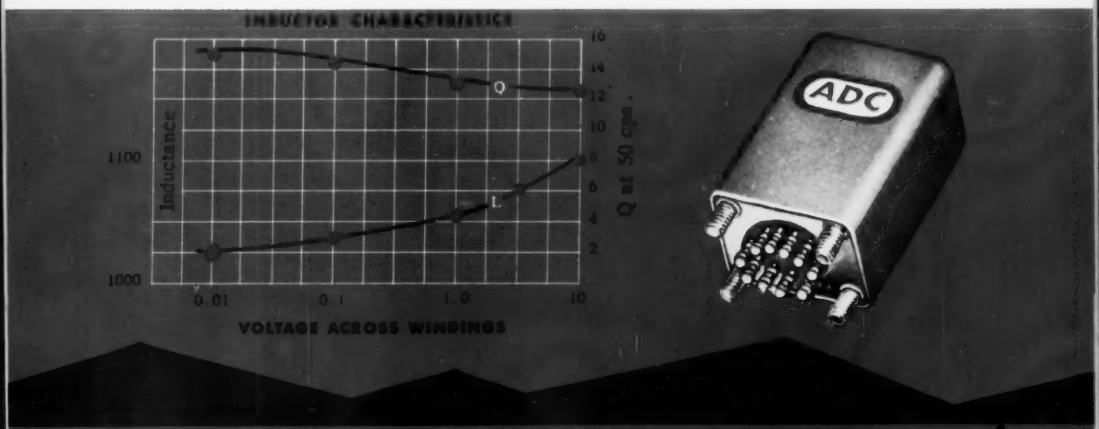
Input and output transformers are of hum-bucking construction—all types are available in steel or mu-metal cases. The 18 units listed on the following page are particularly suited to geophysical, transistor, or other sub-miniaturized application; and are typical of ADC engineering and production techniques in the custom iron core component field.

ADC **AUDIO DEVELOPMENT COMPANY**

1830 Fourteenth Ave. So. • Minneapolis 7, Minnesota • Dupont 7-2881

TRANSFORMERS • INDUCTORS • FILTERS • PLUGS • PATCH CORDS • JACKS • JACK PANELS

LISTED BELOW: are 18 typical sub-miniature transformers and chokes available as stock items in production quantities. Others may be designed to specifications for general audio and carrier frequency equipment. Power level for voice range without unbalanced DC, up to 3-5 watts, or for single tube output, up to 1 watt. All listed units in mu-metal cases except 320Y and 320Z. Curve below showing Hi-Q, low frequency inductance illustrates the unusual characteristics of a typical inductor.



SPECIFICATIONS

INPUT TRANSFORMERS

Catalog No.	Primary Impedance †		Secondary Impedance †	Primary Inductance (±5% at 10 mv 50 cps.)
220A	500 (125) ohms	to	150,000 ohms CT	8.5 hy.
220B	60 (15) ohms	to	150,000 ohms CT	1.0 hy.
220C	500 (125) ohms	to	300,000 ohms CT	8.5 hy.
220D	60 (15) ohms	to	300,000 ohms CT	1.0 hy.

OUTPUT TRANSFORMERS

				(±5% at 1 v 50 cps.)
320A	20,000 ohms CT	to	16/8/4/2 ohms	310 hy.
320B	20,000 ohms CT	to	16/8/4/2 ohms	1200 hy.
320C	20,000 ohms CT	to	16/8/4/2 ohms	1750 hy.
320D	20,000 ohms CT	to	500 (125) ohms	1750 hy.
320E	20,000 ohms CT	to	50/25/12½/6.25 ohms	1200 hy.
320F	20,000 ohms CT	to	50/25/12½/6.25 ohms	1750 hy.
320Y	15,000 ohms CT	to	600 (150) ohms 2 watts	1 db—250—15,000 cps.
320Z‡	10,000 ohms (10 MA DC)	to	600 (150) ohms ½ watt	1 db—300—10,000 cps.

INDUCTORS

	Inductance	Percentage Taps	Q at 0.1 v 50 cps.
420A	1050/800/550/400/280 hy.	None	1050 hy.-11, 280 hy.-8
420D	1500 hy.	3—2%	12
420E	1000 hy.	3—2%	12
420F	850 hy.	3—2%	12
420G	600 hy.	3—2%	12
420H	500 hy.	3—2%	12

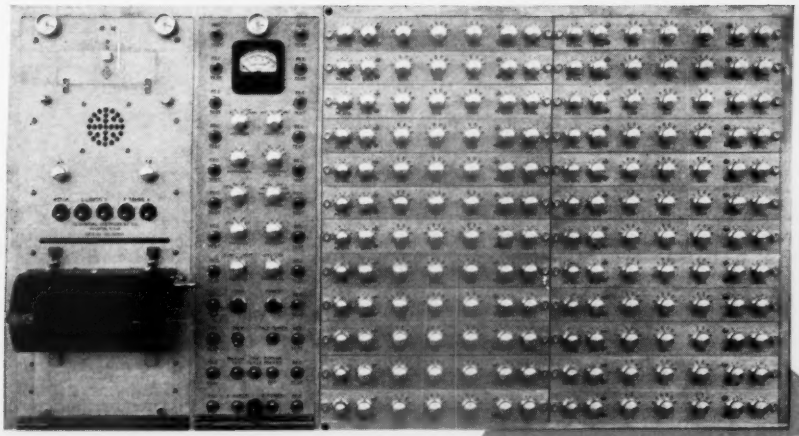
Inductance of middle tap is nominal ±2% at 0.1 volt, 50 cps.

†Impedence in parenthesis indicates parallel windings ‡Single plate, all other transformers push-pull.

ADC AUDIO DEVELOPMENT COMPANY

2833 THIRTEENTH AVE. SO. • MINNEAPOLIS 7, MINNESOTA • DUPONT 7386

TRANSFORMERS • INDUCTORS • FILTERS • PLUGS • PATCH CORDS • JACKS • JACK PANELS



TIC 621 AMPLIFIER

The Technical Instrument Company 621 Amplifier features the most modern design in the seismic field. It provides the maximum in selectivity, sensitivity, and range to make possible the mapping of extremely difficult areas with a high degree of accuracy.

Among its features are: Wide band frequency response, total distortion of less than 1%, choice of one or two each five position low cut and high cut filters, AGC range of one-half microvolt to one volt input, independently adjustable attack and release time constants, three types of gain control (AGC, Expander, or both), by-passed first breaks.

The standard 621 Amplifier system, as shown, consists of 24 channels of amplification, control panel, and six-inch camera. The packaging of this system is of fabricated anodized aluminum construction with stainless steel cover. Dimensions are 36¼" width x 13⅛" depth x 19" height. This system is also available with cameras handling paper widths of 6, 8, 10 or 12 inches, or packaged in units for portable operations.

Technical Instrument Co.

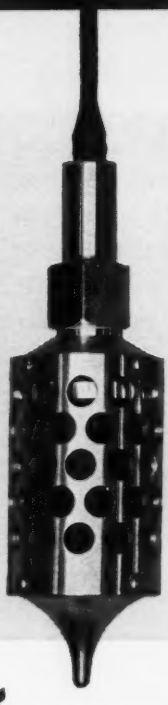
Division of Brush Electronics Co.

3732 WESTHEIMER • HOUSTON, TEXAS

MODEL 321 PRESSURE GEOPHONE. A NEW DIMENSION IN SEISMIC DETECTION
FOR IMPROVED WATER AND MARSH WORK

1) HIGH SIGNAL-TO-NOISE. — Uses self-generating piezoelectric ceramic element. A true pressure phone.
2) COMPACTNESS — Less than 4¼" x 2¼".
3) LIGHTNESS — Approximately 2 lbs. including spike, protective housing and coupling.
4) FLEXIBILITY — Designed to be used in water, either hanging or taped, or in soft marsh. Output impedance and other characteristics chosen for use in any combination of units per trace.
5) MECHANICAL STRENGTH AND STABILITY — Completely waterproofed and coupled to sea by rubber casing and protected mechanically by brass housing.
6) CONVENTIONAL RESPONSE — Designed to have response curve and characteristics similar to conventional 30 CPS dynamic phone.
7) PROVEN RESULTS — Have already provided good usable traces in areas previously considered no record or poor record areas.

The basic 321 design permits the use of multiple elements in a single housing.



MODEL 241-LP PLASTIC LAND SEISMOMETER

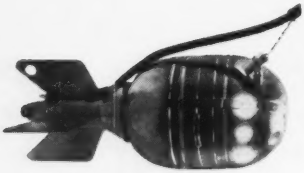
2¼" Maximum O. D.
2" Height
12½-oz. Weight
(Includes Lead & Spike)

This land-type seismometer features newly designed plastic covering which provides maximum protection against sharp shock and abrasion. With the lead outlets near the bottom of the case, the effect of wind noise is practically eliminated. The extreme visibility of the yellow plastic covering minimizes field loss of the seismometers.

The newly designed case has made it possible to use an exceptionally strong lead. It consists of two 3/64" Copperweld conductors in a ⅛" diameter low temperature plastic jacket. Destruction tests of the seismometer lead and jacket indicate a trouble-free service of several years.

SPECIFICATIONS:

Frequency: 15 to 40 cycles accurate to within 1 cps.
Damping: As specified.



FLOATING SEISMOMETER

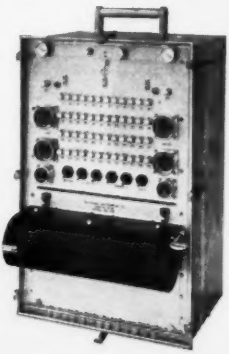
For superior operation in shallow bays where heavier inline drag cables cannot be used we recommend the Floating Seismometer, 241-F, with special stabilizing and lifting design. The special TIC damping feature which eliminates high frequency chatter is one of the main reasons why most operators prefer this seismometer.

90 VOLT BLASTER

This 90-volt blaster will fire a maximum of 6 caps. In addition to regular blaster features it has built-in communication system, 2 button firing, cap testing circuit with meter, and time break adjustment (a pulse less than 6 milliseconds long will produce a break clearly defined).

50 TRACE OSCILLOGRAPHS

TIC Recording Oscillographs are available with or without Galvanometer level controls on the front panel. When the water-tight stainless steel lid is in place, all controls, switches and plugs are protected. Designed for long service with minimum maintenance.

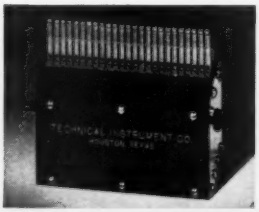


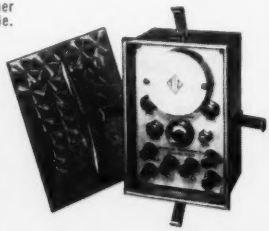
MARSH SEISMOMETER

Used in multiple strings, the TIC Marsh Seismometer, 241-ML, simplifies field checking. Here expensive external strain members may be eliminated since conductors and anchor are rated at 300 lbs. tensile strength. Fitted with a solid brass or aluminum housing case. A waterproof plug-in connection with an "idiot-proof" method of polarization. These seismometers are getting records in some areas previously considered NR (no record). 1½" x 6" — wt. 20 oz. — any reasonable length leads provided.

6 TO 50 ELEMENT GALVANOMETERS

High quality — low cost multiple element Galvanometers. The standard 15 ohm 140 cycle element gives 7" deflection per milliampere at 12". The spherical mirrors have a 10" radius of curvature. First surface .040" wide x.115" long. Other focal lengths and frequencies available.





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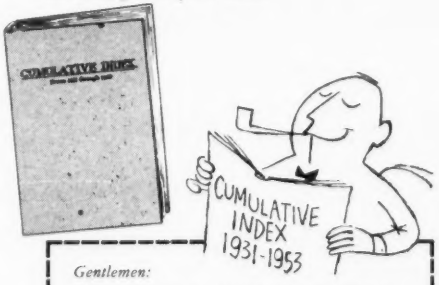
Filbert was buried under a ton of detail — and every ounce of it urgent — when the boss stormed in with the old Poppy Field on his mind. There was a case history on that field . . . came out around 1932, he thought . . . find that paper, Filbert. And, Filbert, find it by five o'clock. Understand, Filbert?

Filbert stared blankly into space. A dull film clouded his eyes. Surely, with luck, he would be dead in five minutes. But visions of his widowed wife and fatherless children pulled him to his feet and sent him trudging out the door . . . to the library.

It would take all day. He'd be spending valuable time his company could hardly afford. And he'd be using all his exploration skill to locate that blessed paper — not to mention structures . . . Filbert stopped at a drug store and bought $4.00 worth of aspirin.

Had Filbert spent that $4.00* on the CUMULATIVE INDEX, he would have saved himself that headache and many, many more. The S.E.G. CUMULATIVE INDEX 1931-1953 is a complete library on geophysical data at the tips of your fingers. Remember, a man is as useful as the knowledge he possesses. The CUMULATIVE INDEX is knowledge on your desk!



Gentlemen:

Please send me the CUMULATIVE INDEX, 1931-1953.

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( ) Bill me, plus postage.

( ) Bill my company, plus postage.

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COMPANY.....

ADDRESS.....

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*$3.00 to SEG members

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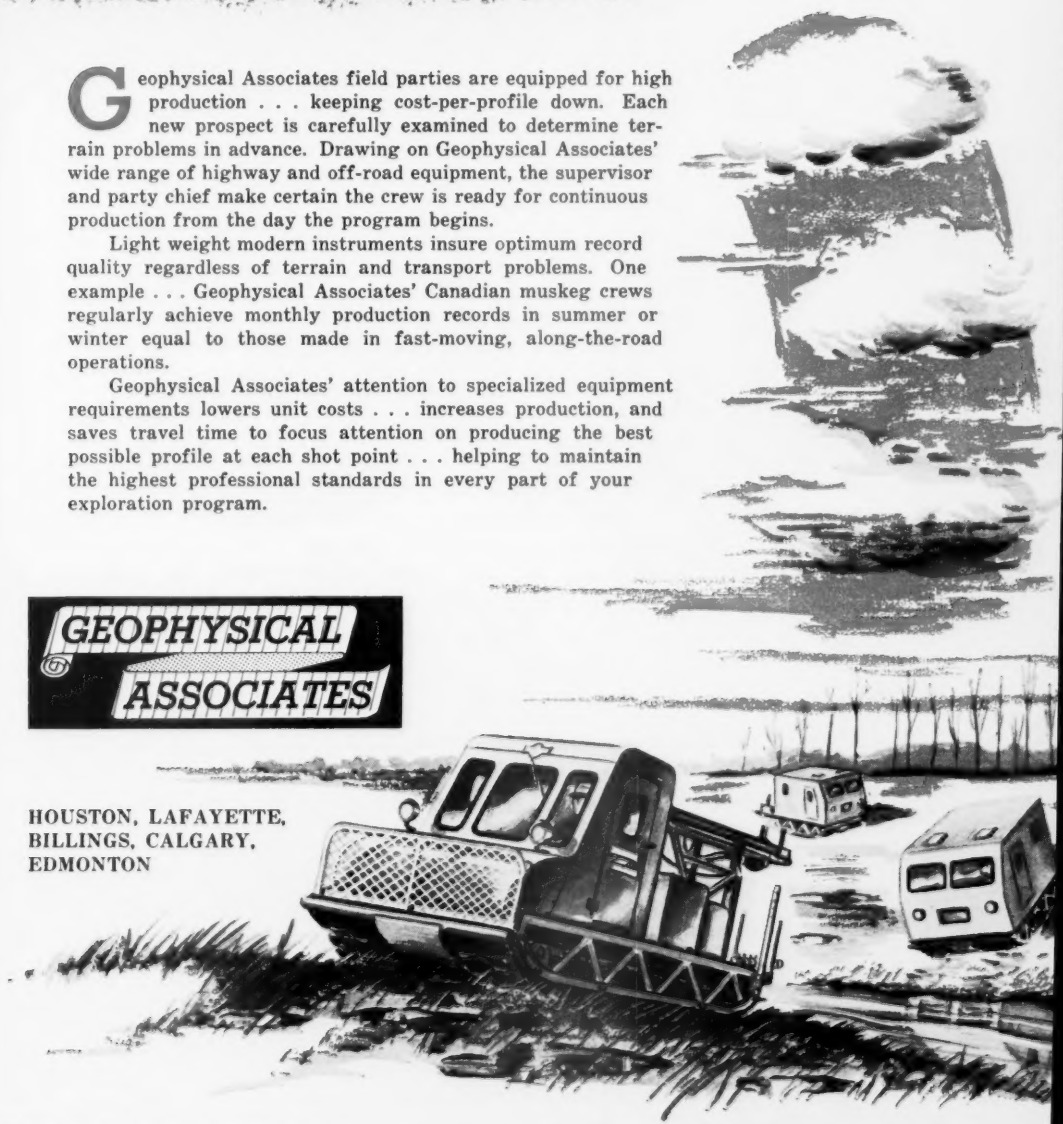
Geophysical Associates' attention to specialized equipment requirements lowers unit costs . . . increases production, and saves travel time to focus attention on producing the best possible profile at each shot point . . . helping to maintain the highest professional standards in every part of your exploration program.



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✓ **CONTAINER FLOATS**—If accidentally dropped into water, records and papers are safe. And the bright red can makes for easy spotting and quick pickup.

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As important as is this new Seismo-Writ canister, the real story lies in the paper itself. New Seismo-Writ is 50% faster than before. With this new high-speed paper, you'll get clear, sharp records of every shot; even the slightest "kicks" show up as dense, black traces on a clean, white background.

You can use lower lamp voltages with new Seismo-Writ. And with lower lamp voltages, you get longer lamp life, too, . . . fewer shots lost because of bulb failure.

Speed isn't all that's been improved with new Seismo-Writ. It develops faster, too . . . 15 to 20 seconds does it. Crews can pick up and move to the next shot quickly.

New Seismo-Writ is rugged. Whether you're shooting offshore, deep in the bayous, or out in rough country, you'll get clear, uniform records. Even "sweep" traces and timing lines stand out against a clean, white background.

New Seismo-Writ is available in two types—durable, standard weight Type B, and extra-thin, translucent Type W, an all-rag paper with extremely high wet and dry strength.

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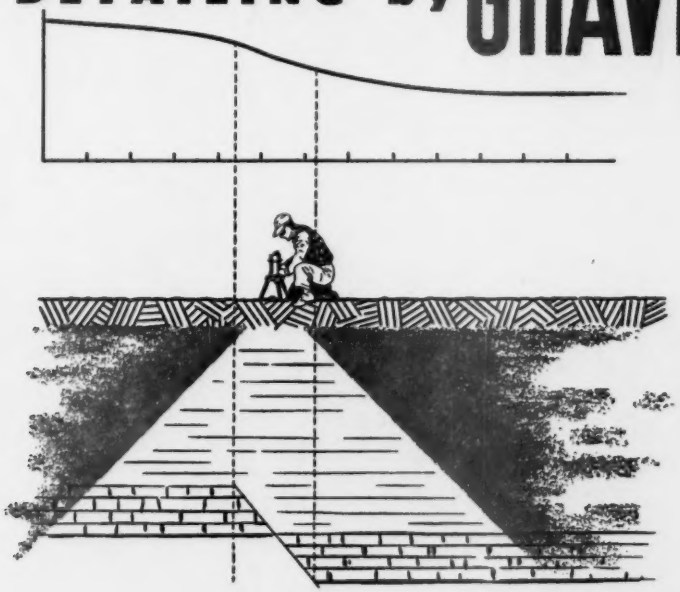

The basic information obtained from an SSC Gravity Survey are maps of the gravity variations and a report on their significance to "oil finding."

The data on these maps is processed by the geophysicist so that the density variations thereon, are related to the geology of the area. In the report, their consequence to "oil finding" is interpreted by the geophysicist in co-operation with the geologist.

Detailed *gravity surveys* are recommended for these typical situations.

1. Where the area to be mapped does not justify the expense of a detailed seismic survey.
2. Where the seismograph is not effective, and
3. Where mappable density changes are directly related to geology such as:
   - Reefs, either bioherms or biostromes,
   - Salt domes,
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   - Density contrasts caused by faulting.

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